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RECENT PHYSICAL RESEARCH.

AN ACCOUNT OF SOME RECENT
CONTRIBUTIONS TO EXPERIMENTAL PHYSICS.

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PREFACE.

THE present-day student of Physics soon becomes aware of the fact that important contributions have been added to this branch of knowledge in recent years, which are barely if at all referred to in general treatises. The text-book, even when fresh from the press, is, perhaps necessarily, several years behind the wave-front of advancing knowledge. Attention is liable to be especially long withheld in the case of work done outside one's own country.

An attempt is here made to give a connected description of the ground covered and of the paths of advance in some of the recently acquired provinces of Physics. The book is based on a series of bi-monthly articles, under the same title, which appeared in "The Electrician" in 1910 and onwards. The author desires to express his thanks to the Editor and to the Publisher for placing the text of the articles and the blocks used for the illustrations at his disposal.

London, September, 1913.

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CHAPTER I.

POSITIVE RAYS.

§ 1. As Helmholtz and Maxwell independently remarked, Faraday's laws of electrolysis point to the conclusion that atoms of electricity exist just as surely as do atoms of matter. In liquids the ratio e/m of charge to mass is known to vary with the chemical nature of the ion, being greatest (nearly 10^4 E.M. units of electricity per gramme) in the case of hydrogen. The carriers of negative electricity in liquids are never less than atomic in size. In gases, on the other hand, during the passage of a current, we now know that there are present negatively charged particles of mass far smaller, namely, some $\frac{1}{1700}$ part of the mass of the H atom; moreover, these particles are the same no matter what the gaseous molecule from which they have been extracted. The mass of these negative particles appears to be purely electrical in origin; for it is found by experiment to increase with the speed in a way that had already been predicted of an electric charge in a classical Paper published by Sir J. J. Thomson in 1881. Again, the effect of a magnetic field on the light emitted by a gas (the Zeeman effect) is evidence of the presence of negatively charged particles associated with the light-giving molecules; and exact measurements establish very conclusively the identity of these particles with those found in the electric discharge in gases at low pressures. The phenomena of the conduction of electricity and of heat in metals have been correlated on the assumption of the presence of these free electrons or corpuscles within the inter-molecular spaces of the metal.

**The
Electron or
Corpuscle.**

§ 2. The existence of the negative electron, or corpuscle, may now be regarded as firmly established. One or more corpuscles may be abstracted from a molecule; the molecule is then said to be positively charged. What is this positively charged residue? Is the negative the only kind of *electricity*, the rest of the molecule being *matter*? Or is there a charge of *positive electricity*, distinct from the *matter* of the molecule? Or is the

**The
Positive
Unit.**

residue left on separation of the corpuscle *positive electricity*, possessing, like the negative, inertia? The first and third questions are clearly one and the same; an affirmative answer would mean that the molecule was composed simply of negative and positive electricity, all the properties of the molecule, including its mass, being explicable in terms of electricity.

Accepting, then, the existence of the negative electron as proved, the question arises as to what fraction of the mass of the molecule is due to the electrons present. In June, 1906, Sir J. J. Thomson advanced three lines of argument, based on experimental data, all leading to the conclusion that the number of corpuscles in the atom is of the order of its atomic weight. The number in hydrogen would be one, or at all events not a large multiple of one, in the mercury atom 200, and so on. In view of the small mass of the corpuscle it appears that by far the greater part of the mass of an atom resides in the positively charged residue. What, then, is the constitution of this residue? Is it composed of small units which, like the electron, are the same for all substances? If so, what is the charge of this unit and its associated mass? Attempts towards the elucidation of these questions have been made mainly by examination of the mechanism of the passage of electricity through gases. These investigations show that in a vacuum tube there are rapidly moving streams of positively electrified particles, corresponding to the now well-understood streams of electrons or cathode rays.

Positive Rays.

§ 3. These positive streams were first observed by GOLDSTEIN in 1886, being called Canal rays. They are seen streaming through a hole in the cathode in a discharge tube, their direction being perpendicular to the front surface of the cathode and away from the anode. Similar rays are seen streaming from the cathode in the opposite direction, from cathode towards anode; these are Goldstein's K_1 -rays, also since denoted by the term "retrograde rays." In all, Goldstein specifies five types of positively charged ray in the vacuum tube. In hydrogen the canal and the retrograde rays—to specify the chief types—are rosy red in colour; in air they are blue. They cause metallic salts on which they impinge to emit the characteristic light of the metal—*e.g.*, sodium salts glow with an intense yellow light, salts of lithium with a red light. When

they fall on thin metallic films the films are disintegrated. Later on, in 1906, REICHENHEIM discovered the Anode rays, consisting of rapidly moving, positively charged particles starting from the anode, one stream moving forward towards the cathode, a second stream in the opposite direction.

These various streams of positively charged particles may conveniently be grouped together under the title of POSITIVE RAYS, as suggested by Sir J. J. Thomson.

§ 4. Whilst Goldstein traced the direction and apparent place of origin of positive rays, WIEN made measurements of the ratio of charge to mass and of their velocity. The measurements disclosed the fact that the positively charged particles concerned differ essentially from the negative electron in having large masses of the order of the mass of the atom.

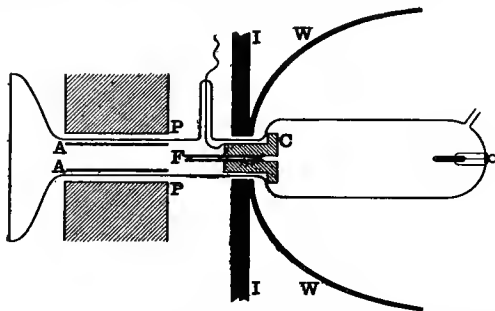


FIG. 1.—POSITIVE-RAY TUBE.

C—cathode. F—canal-ray tube. AA—the electrostatic plates. PP—the magnetic poles. II and WW—iron plates to screen the cathode space from the field of PP. ("Phil. Mag.", Oct., 1910.)

In 1907 Sir J. J. THOMSON began a series of important contributions to our knowledge of these rays. Of this work we will proceed to give a brief account. The canal rays are found to possess speeds of the high value 2×10^8 cm. per sec.—that is, nearly one-hundredth the speed of light—a speed which, though enormous, is yet inferior to the speeds attainable in the cathode rays (6×10^9 cm. per sec.). The values of the e/m ratio and of the velocity are obtained from the deflections produced by the combined application of known magnetic and electric fields, the rays being received on a Willemite phosphorescent screen. The tube used is shown in Fig. 1. The first

**Early
Work of
Sir J. J.
Thomson.**

series of experiments ("Phil. Mag.", May, 1907, and September, 1907) showed that the particles in the canal rays were of two kinds, the value of e/m for one set being 10^4 , for the other $10^4/2$. The remarkable result was found that these values are the same no matter what the gas in the tube may be, whether hydrogen or oxygen, or heavy vapours like CCl_4 or UrCl_4 . They are seen to be the same as for the atom and the molecule respectively of hydrogen, if we suppose that the charge carried is the same in each case as that carried by the H atom in the electrolysis of liquids. Careful and prolonged experiments confirm the fact that these values are found when special means are taken to exclude hydrogen from the tube. Or, to reverse the procedure, starting with a gas entirely free from hydrogen, it appears that the gradual introduction of hydrogen does not affect the character of the phosphorescence produced by the deflected beam. If, for example, oxygen be used, no particles are observed whose e/m ratio equals $10^4/16$ or $10^4/32$ —that is, involving an atom or molecule of oxygen. The retrograde rays by a similar examination appear to be of one kind only—namely, positively charged particles having the same speed (2×10^8 cm. per sec.) as the canal ray particles, but with the larger value of e/m —that is, 10^4 .

It will be seen that these results strikingly resemble those now familiar in the case of the cathode rays. The rapidly moving particles constituting the canal rays appear to be independent of the nature of the gas in the discharge tube. Sir J. J. Thomson was thus led to propose the view that we have here proof of the existence of a definite *unit of positive electricity*, which can, like the corpuscle, be detached from the molecule.

The immediately succeeding Papers of Sir J. J. Thomson are largely concerned with the manner of production of the positive unit from the molecule. One striking experimental result is that the kinetic energy of each particle in the rays is many times greater than the work that would be done upon it in virtue of its fall down the electric field in the tube. This velocity is practically independent of the fall of potential across the tube. A total fall of 3,000 volts produces the velocity 2×10^8 cm. per sec., which a simple calculation—equating Ve to $\frac{1}{2} mv^2$ —shows to correspond to a potential drop of 20,000

volts. The P.D. could be increased from 3,000 to 40,000 volts without any apparent effect on the velocity. The view is therefore taken that a molecule of gas in the discharge tube receives energy from the collisions with it of the cathode-ray particles. This energy the molecule accumulates until the point of explosion is reached, when a "neutral doublet," composed of one unit of positive electricity and a corpuscle, is shot out at high speed.

The canal and retrograde rays are, on this view, regarded as consisting, at their inception, of neutral doublets. Their high speed renders them comparable with the particles of a gas at very high temperature, say some hundreds of thousands of degrees Centigrade. Dissociation may take place, resulting in the production of particles of free positive and negative electricity respectively. These in their turn may re-combine to a neutral doublet; or the neutral doublet may unite with a

**The
Neutral
Doublet.**

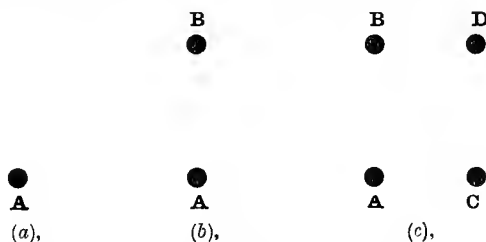


FIG. 2.

corpuscle to form a negatively charged particle of mass practically unaltered, since the mass of the corpuscle is almost negligible. The canal and retrograde rays would thus be composed of charged particles, negative as well as positive, whose e/m ratio is 10^4 , and of neutral doublets. The facts of dissociation and re-combination are clearly shown by the following experiments. A beam of canal rays is subjected to two magnetic fields in succession, their directions being perpendicular to each other and to the direction of the rays. The first field may be placed near the cathode, the second further along the beam, which goes on and impinges upon the phosphorescent screen. The effects on the screen may be represented as in Fig. 2: (a) represents the bright spot A on the screen before either magnetic field is on; (b) represents the effect of switching

on the first field. Two spots are now seen, one at A in the undisturbed position, the other at B, whose deflection corresponds to the ratio $\frac{e}{m}=10^4$. The spot A is produced by rays unaffected by the field, therefore presumably uncharged while passing through it; (c) represents the effect when both fields are on. The undeflected spot A is still seen, corresponding to particles that have remained uncharged in the whole of their path. A new spot appears at C, showing deflection by the second field of particles which have acquired their charge since leaving the first field. A spot still persists at B, proving that particles which were charged in their passage through the first field have lost their charge in the space intervening between the two fields. The spot at D is due to particles which have kept their charge from the first field to the second. The equality of the deflections AC and BD proves the equality of speed and e/m ratio of the two sets of particles concerned. Here we have simple evidence of the dissociation and re-association of oppositely charged particles which, on the view here considered, are the units of positive electricity and corpuscles respectively.

The "neutral doublet" has been invoked also in the explanation of the mechanism of ionisation in gases at higher pressures under the influence of X-rays, &c. The experiments of Wellisch ("Proc. Roy. Soc.", July, 1909) show that the velocity of positive ions in a mixture of a heavy gas, say CCl_4 , with hydrogen is practically the same as that of a charged hydrogen molecule, though the direct dissociating effect of the ionising agent is almost solely confined to the heavier molecules. It is considered impossible that the large molecule, minus a corpuscle, could transfer its positive charge to the smaller one, as an increase in potential energy would be involved. The results are in harmony with the view that the act of ionisation consists in the ejection from the molecule of a Thomson neutral doublet which breaks up into the positive unit of electricity and a corpuscle, these then uniting with the molecules present in the gas to form the moving ions.

§5. This account of the views held by Sir J. J. Thomson cannot be said to give a very clear perception of the nature of the positive unit. The high-speed positive particles in the

vacuum tube are independent of the gas whence they are produced. The ratio of charge to mass is known, but not the absolute value of either. Whether the value of the charge of the positive unit is equal to that of the negative electron is not determined. The ratio e/m is the same as for a H atom in the electrolysis of acidulated water. Does this mean that a hydrogen molecule is composed of two units of positive electricity and two corpuscles? Again, if the preliminary to ionisation of the molecule is extrusion of a fundamental constituent of all molecules, namely, the neutral doublet, with subsequent decomposition of the latter one would expect to find positive particles of $e/m=10^4$ amongst the rays emitted by radioactive bodies. Prof. Rutherford's remarkable series of experiments on the α -particle prove that this body is a positively charged atom of *helium*: that is, a particle whose mass is about four times that of the hydrogen atom, although the velocity of the particle (10^9 cm. per sec.) is many times greater than that of the high-speed positive rays in the vacuum tube.

§ 6. Other lines of experimental research which have a bearing on the question of the existence of a free positive unit of electricity may be touched upon. It is well known that the Hall phenomenon varies in sign in different metals. The same remark appears to be true of the Zeeman effect. This effect of a magnetic field on the period of vibration in line spectra has been explained satisfactorily in terms of the electron, the e/m ratio deduced from the observed displacement of the lines working out to be equal to that obtained in experiments in the gas discharge tube and on the β -rays emitted by radio-active bodies. JEAN BECQUEREL (1909) has shown that the Zeeman effect applies also in the case of the absorption bands of some crystalline bodies and their solutions. Furthermore, he records that he has observed a reversal of sign; that the sign of the accelerated circularly polarised component, as viewed *along* the direction of the magnetic field, is in some cases opposite to that hitherto observed. This result is confirmed by DUFOUR in the case of certain gaseous emission spectra. In the previous year Prof. R. W. WOOD had discovered a *positive* rotation in the case of some of the absorption bands produced when plane-polarised light is passed through sodium vapour in a magnetic field. If the normal effects in the above-men-

**Other
Lines of
Research
on the
Positive
Unit.**

tioned classes of phenomena are due, as has been supposed, to the presence of negative electrons, the question arises whether the reversed effects are to be taken as implying the presence of positive units corresponding to electrons.

Mention may be made, too, of the discovery by STARK, of Göttingen, of the Doppler effect in the light emitted by the positive rays in a vacuum tube discharge. Measurements of this effect led to the determination of the speed of the particles emitting the light, and seem likely to contribute to our knowledge of positive electricity.

CHAPTER II.

POSITIVE RAYS (*continued*).

§ 1. A considerable amount of work of great interest has been done on the subject of the positive rays in the course of the last three years. In gathering together the new issues that have arisen, the new experimental methods of attack, and the results that have accrued, one feels the appropriateness of a remark of Goldstein's. In 1908 Goldstein published an English translation of his work up to 1902, representing the main results of 16 years' observation on these rays. He expressed in a footnote to the Paper the hope that this reprint would prove to the reader that "canal rays are a much more complicated phenomenon than generally admitted." In recent years the number of workers has steadily grown: the subject has been taken in hand by a great number of distinguished workers both in this country and in France and Germany. The collision of views as to the proper interpretation of phenomena which appears in the published records is an eloquent confirmation of Goldstein's sense of the peculiar difficulties of the subject. Some very definite facts, however, have been established, which show that a great field of work of the highest importance is here under exploration. Attention will be directed in this article mainly to the work of Sir J. J. Thomson in the Cavendish Laboratory; briefer reference will be made to the work of W. Wien, J. Stark and other experimenters.

§ 2. The properties of the rays may be first briefly characterised, the description being limited to the class of rays of greatest importance, on which by far the greatest amount of attention has been concentrated, namely, the canal rays. These rays in the main originate in the negative glow—that is, just beyond the Crookes' dark space. In this region positively charged particles of atomic or molecular dimensions are present, which move with acceleration in the electric field. On arrival at the cathode, with high velocities depending on the potential fall, a bundle of these moving particles is admitted through a

**Summary
of Properties
of Positive
Rays.**

fine tube set perpendicular to the cathode, and continues its course in the space behind. When these rays impinge on certain materials they produce phosphorescence. Sodium salts show a brilliant yellow coloration, lithium salts a red. Willemite is extremely sensitive to the rays, giving a brilliant bluish-green glow.

The rays affect a photographic plate, the action being apparently greater the faster the ray. The heating effect on an obstacle is large. They are deflected by both electric and magnetic fields, a narrow bundle being spread out into a band, thereby evidencing the heterogeneity of the constituents. All the above-mentioned properties have served as the basis of quantitative observation. Some of the particles are charged with positive electricity, some with negative (the number of these being generally, perhaps always, less than that of the positive), whilst a large proportion are electrically neutral.

They produce ionisation of the gas which they traverse. They possess speeds up to 2×10^8 cms./sec., which is the value attained in hydrogen under the highest potential falls that are used. The track of a bundle is luminous, and if viewed in the direction of its length shows the Doppler effect—this property, too, serving as a basis of quantitative estimation.

The chemical constitution of the particles depends on the gas present in the tube. Under the influence of the electric discharge violent disruption of molecules takes place: for example, in the case of benzene vapour some 17 different carriers of positive electricity have been observed. The sorting out by magnetic and electric fields constitutes a novel method of chemical analysis, revealing not only the nature of atoms and molecules but also of the fractional parts into which the latter may be decomposed.

An essential distinction between these rays and cathode rays—apart from that of sign of charge—is the fact that the electric charge of the positive rays is never associated with any portion of matter smaller than the atom. The hydrogen atom is thus the lightest positive particle encountered.

Atoms, with the exception of hydrogen itself, are capable of taking up sometimes more than one unit of positive electricity (the unit=charge of the hydrogen charge in electrolysis of water). In the case of mercury the number of charges may

be as great as eight. *Molecules* appear never to be multiply-charged.

§ 3. *Experimental Methods of Study.*—The chief metrical **Experimental Methods.** methods which have been employed are as follows :—

(1) *By the heating effect.*—The rays are drawn out into a band by a magnetic field, and allowed to fall on a linear thermopile set perpendicular to the band, and capable of screw motion perpendicular to its length. Thus the energy of the different constituent particles may be compared. This is the method recently employed by Wien.

(2) *By the use of parallel coterminous steady magnetic and electric fields.*—The rays are thus sifted into a kind of spectrum of parabolic bands, which are studied either by means of a willemite phosphorescent screen, or by a photographic plate, or by the Faraday cylinder. These are the methods which have been adopted by Sir J. J. Thomson.

(3) *By the Doppler Effect.*—The canal-ray beam is examined in the direction of its length by the aid of a prism spectrograph, or a metallic grating of high dispersive power. Using a photographic plate two sets of spectral lines appear: the “stationary” set, the lines in which coincide with those obtained when the collimator is set perpendicular to the beam; and the “displaced” set, the lines of which are to the violet side of the corresponding stationary lines. Measurements have been made by Stark, Paschen, and Reichenheim and Gehrcke.

SIR J. J. THOMSON'S EXPERIMENTS.

§ 4. It will be seen from the preceding chapter that Sir J. J. Thomson's earliest work was mainly concentrated on the attempt to prove the separate existence of a definite carrier of positive electricity, independent of the chemical nature of the gas used in the discharge tube. Strong evidence was adduced that such a particle exists, the ratio of its charge to its mass being identical with that of the hydrogen atom in electrolysis of a liquid, viz., 10^4 E.M. units. The phosphorescent screen proved that in spite of extraordinary care to clear hydrogen out of the tube particles of the above kind manifested their presence, whilst no evidence of the existence of heavier atoms was

only showed the presence of bands due to hydrogen and helium. Fresh parabolic bands now made their appearance, due to carbon, oxygen, neon, mercury, &c.

Another important step was the substitution of the photographic plate for the phosphorescent screen. Plates could be enclosed in a light-tight metal case within the tube and moved into position for exposure to the rays by the rotation of a perfectly fitting glass stopper (*see* Fig. 4). It was found that after only three minutes' exposure to the rays bands appeared

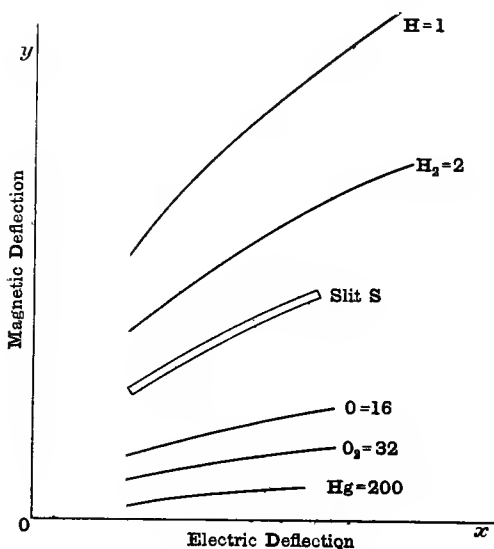


FIG. 3.—PARABOLIC BANDS.

Equal minimum electric deflection. The parabolic slit S is employed in conjunction with the Faraday cylinder.

on the plate after development, of which no trace was to be seen on the willemite screen. Much finer beams could now be worked with. Tubes of copper drawn out to diameters between 0.1 mm. and 0.01 mm., and about 8 cm. in length, were used. Later a very fine channel was obtained by making a fine scratch on a truly plane steel plate which was bolted down to a similar plate; in this case exposures of from two to three hours were

found necessary, special care being taken to maintain invariable the P.D. across the discharge tube and the strength of the deflecting fields.

A quantitative method of attack was next added, namely, the determination by the Faraday cylinder of the charge carried by the particles. The tube with cylinder attached is represented in Fig. 5. The rays after passage through the combined magnetic and electric fields was allowed to fall on a parabolic slit cut in a metal plate. Behind the slit

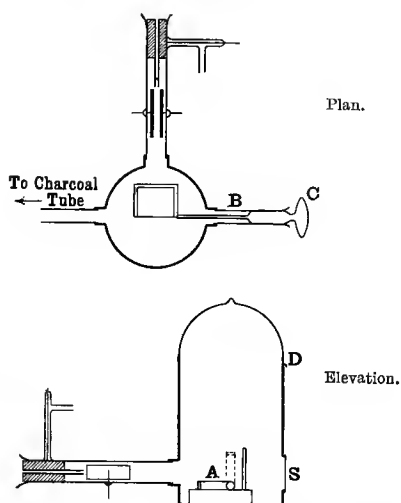


FIG. 4.—ARRANGEMENT FOR PHOTOGRAPHING THE RAYS.

("Phil. Mag.," Feb., 1911.)

was the insulated Faraday cylinder into which the particles entered, carrying with them their charges. From the rate of increase of potential of the cylinder (a Wilson tilted electroscope was used) the actual number of charged particles could be deduced. By reference to Fig. 3 it will be seen how by suitably varying the magnetic field each parabolic band in turn could be made to cover the slit S.

The combination of the photographic method and the

Faraday cylinder thus enables at the same time a qualitative and a quantitative analysis of the gases in the tube to be made.

§ 7. The main results of Sir J. J. Thomson's work will now be considered.

Multiply-charged Atoms.

(1) *Multiply-charged Atoms*.—Fig. 3 represents the appearances seen on the photographic plate when all the particles possess a single unit positive charge after as well as before passage through the cathode. It is found, however, that atoms of all gases, with the exception of hydrogen, are capable of possessing two or more unit charges in their fall through the cathode dark space. They thus pass through the cathode with an amount of kinetic energy which, by equation (iv.), is

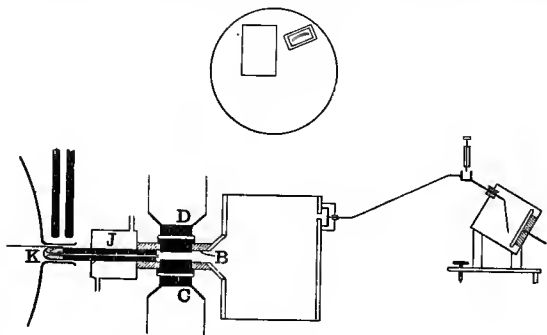


FIG. 5.—POSITIVE-RAY TUBE WITH FARADAY CYLINDER ATTACHMENT.
("Phil. Mag.," Aug., 1912.)

C and D—pole-pieces of the electromagnet, the opposed faces of which act as boundaries of the electric field. B—cylindrical box, in end of which parabolic slit is cut (see upper figure). J—water-jacket. K—cathode.

greater in proportion to the charge. In the deflectional chamber one or more of these unit charges may be lost. Thus, for example, oxygen atoms may carry a single charge on both sides of the cathode; they will lie on the parabola for which $m/e=16$. They can also carry a double charge in the dark space, arriving at the cathode with twice the kinetic energy of the former set; but after passage through the cathode they may proceed through the deflecting fields with only one unit of charge left. Both sets will lie on the same parabola, but the

electric deflection corresponding to O^{++} will be half that of O^{+} . The number of particles of the former class is generally small, and the effect on the plate is to give a kind of beaked appearance to the parabola as shown in the diagram of Fig. 6. Fig. 7 is taken from an actual photograph. There may be particles which retain both charges in the deflecting field, and these will produce a different parabola whose head is in the normal position, the ordinates being $\sqrt{2}$ times those of the former curve.

Argon and nitrogen show triply-charged atoms, the former very distinctly; whilst krypton can carry four units of charge.

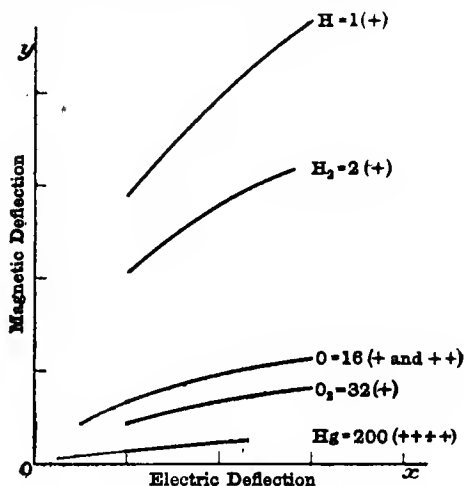


FIG. 6.—MULTIPLY-CHARGED ATOMS.

Mercury is represented in the case where it has four units of charge. The oxygen atom is shown with two units. The molecules (of hydrogen and oxygen) have only unit charge. The hydrogen atom is exceptional in possessing no more than one unit charge.

Mercury is remarkable in giving atoms with eight charges. A sheaf of eight parabolas appears on the photographic plate; showing that particles which in front of the cathode were short of eight corpuscles have proceeded, some without charge, some after regaining one corpuscle, some after regaining two, and so

on to some which have regained all eight and so become neutral again in the deflecting fields. A photograph representing the effect in mercury is reproduced in Fig. 8. The heads of the parabolas coming out most distinctly in the plate lie on a line through the origin, showing that the corresponding particles possessed the same velocity.

**Chemical
Composition
of the
Particles.**

(2) *Chemical Composition of the Carriers.*—If hydrogen is the gas present, $H+$ and $(H_2)+$ are found. At times a band corresponding to particles with electric atomic weight 3 appears, to which some uncertainty attaches. It does not appear if perfectly pure hydrogen is present; it does not therefore seem to be merely an aggregate of $H+$ and H_2 . It is mooted that there may be a new element here, the lowest member of the Cl—F series.

In oxygen the carriers $O+$ and $(O_2)+$ are generally present; $(O_3)+$ and $(O_6)+$ also occur.

Nitrogen exists in a very large number of modifications in the discharge tube. $N++$, $N+$, $(N_2)+$, $(N_3)+$ are always present when the tube contains nitrogen, and on some plates $N+++$, the triply-charged atom, appears.

In carbon monoxide are found $C+$, $O+$, $(O_2)+$, a particle of $m/e=47$ (CO_2 or O_3 ?); $(CO)+$ appears only very faintly on the photographic plate, but its existence in strength is attested by the Faraday cylinder.

In helium are found $He+$ and $He++$; the latter is interesting as being identical in mass and charge (though not in speed) with an α -particle.

In hydrochloric acid the lines of the hydrogen atom and molecule show strongly, that of the chlorine atom faintly (it appears difficult to distinguish between $Cl+$ and $(HCl)+$, or to say that one is present and not the other).

Gaseous compounds containing heavy metallic atoms appear loth to show lines due to the metal. The nickel line has been observed very faintly in $Ni(CO)_4$. It was impossible to observe any effect due to zinc when zinc-ethyl was used.

Mercury vapour appears as an exception to the above rule. The nature of the carriers in this case has already been described.

Bands have been observed which cannot be referred to known bodies. The particle for which $m/e=3$ has already been mentioned. In a recent letter to "Nature," Sir J. J.



FIG. 7.—PARABOLIC BANDS.
(From photograph. "Phil. Mag.," Aug., 1912.)



FIG. 8.—PARABOLIC BANDS IN MERCURY VAPOUR.
(*"Phil. Mag.,"* Oct., 1912.)

Thomson gives reasons for believing this to be an element released from metals and other substances under the influence of cathodic bombardment—helium and neon also escaping under the same process. He tentatively suggests that these bodies owe their presence to a minute degree of radio-active change within the substances treated, the rejected particles, namely, atoms of helium, neon, or the new body X_3 , being entangled in the larger atom, from which they can be released by the impact of cathode particles, though not by heating the substance beyond the melting point.

There is a band corresponding to $m/e=22$; this line does not disappear when the tube is cooled by liquid air, and therefore cannot be assigned to $(CO_2)^{++}$. Again, in some tubes a band $m/e=6$ and another of the value 10 have been observed.

An examination of the heavier residual gases of the atmosphere, isolated by use of liquid air, reveals no band which cannot be accounted for; presumably no heavy gases are left to discover in our atmosphere.

(3) *Data yielded by the Faraday Cylinder Method.*—Up to the present the main teaching of this method is the fact of the great sensibility of the photographic plate and the phosphorescent screen to the lighter and therefore faster-moving particles. This may be shown by considering the curve of Fig. 9, the ordinates in which represent the number of charged particles passing into the cylinder in unit time, the abscissæ the magnetic field required to bring the corresponding parabolic band on to the slit. The gas in the tube was carbon monoxide. It will be seen that the number of CO particles caught is far greater than the number of hydrogen molecules. The number of hydrogen atoms is much less, indeed, too small to represent to the scale chosen; yet the effect of these on the phosphorescent screen is far greater than that produced by CO. Though the Faraday cylinder shows that the number of hydrogen particles steadily falls off with diminution in the quantity of hydrogen admitted to the tube, the phosphorescent effect due to hydrogen remains practically unaffected. The atom of mercury produces a marked effect on the photographic plate and appears at first sight an exception to the rule that the effect increases with velocity; but the exceptional charge of mercury in the

**The
Faraday
Cylinder.**

cathode space explains this—a simple calculation shows that the speed of the mercury atom cannot be much inferior to that of the singly charged atom of oxygen.

**Particles
with
Negative
Charge.**

(4) *Negatively charged Particles.*—The canal-ray beam contains negatively charged and neutral as well as positively charged particles. The neutral particles have become so by gaining one or more electrons soon after passing through the front surface of the cathode; whilst the negatively charged bodies are those which have been able to go a stage further, to attract and hold an additional electron. The latter appear to

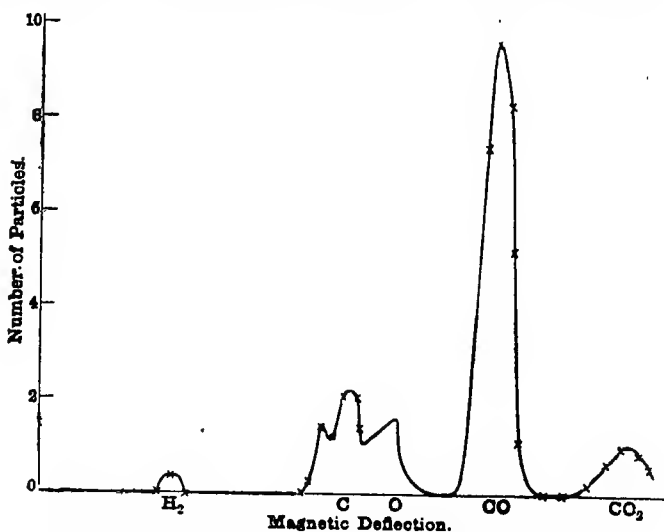


FIG. 9.—RESULTS OBTAINED BY THE FARADAY CYLINDER.
Carbon monoxide in the tube.

be confined to atoms only, hydrogen, carbon, oxygen, sulphur and chlorine being conspicuous by their ability to take up a negative charge; whilst in helium, argon, nitrogen and mercury no negative bands have been observed. The Faraday cylinder method shows that in hydrogen the number of negative atoms is small compared with the number of positive; in the case of oxygen the reverse is the case. It would appear indeed that the atoms of electro-negative

elements acquire a negative charge far more easily than do the other elements. (See, however, the results obtained by Wien in the case of oxygen, which are given below.)

(5) *Place of Generation of the Rays.*—The intensity of the bands is greatest generally at their head, where the velocity is that corresponding to fall through the full cathodic drop of potential. The conclusion drawn is that most of the positive particles are produced at the extremity of or outside the dark space. Experiments by movable screens show that phosphorescence on the side of the screen away from the cathode persists from the cathode up to the negative glow, beyond which it disappears. So far as the rays are due to ionisation by cathode rays this conclusion is borne out by the fact of the considerable degree of uniformity of speed which the cathode rays possess. For if a cathode particle causes ionisation of a neutral molecule within the dark space by the expulsion of a corpuscle, the latter would in its fall through the rest of the dark space acquire a velocity smaller the further the place of collision from the cathode. The cathode rays appear to be generated practically entirely at the cathode under its bombardment by the positive rays.

**Place of
Origin of
Rays.**

On the other hand, the great length of the bands leads to the conclusion that some of the particles are formed at points much nearer to the cathode. The range of velocity depends on the nature of the gas in the tube. In some cases the bands are very short, in others the maximum electric deflection may be five or six times the minimum. These slower rays may be produced by the impact with neutral molecules of positive rays, in the course of their path towards the cathode; or of retrograde ray particles, moving away from the cathode.

We have here considered the origin of the rays before passage through the cathode. Experiments recounted in the previous chapter show that loss or gain of corpuscles may take place in the observation chamber, and such changes are attributable to collision with corpuscles practically at rest. These collisions do not sensibly deviate the canal ray particles.

§8. Some interesting theoretical problems are discussed by Sir J. J. Thomson. We may instance the question of ionisation by cathode particles and by positive rays respectively. It is suggested that the former kind of particle produces ionisation

**Some
Theoretical
Problems.**

by expelling a similar particle from the atom on which it impinges. Corpuscles are minute objects compared with an atom or molecule, and it is urged as unlikely that collision of an atom with a corpuscle could lead to anything more serious than loss of a corpuscle. Positively charged particles, on the other hand, can, owing to their size, deal with atoms or groups of atoms, and may be expected to split up molecules. It is found that in the discharge tube molecules never occur with more than one unit of charge. It seems probable that these ions are produced by corpuscular collision. The act of formation of multiply-charged atoms may be pictured as the collision of a rapidly moving atom or molecule with a neutral particle; which results in the jerking off of a group of corpuscles which were held with the same degree of firmness in the original atom or molecule. Thus in the case of mercury a group of eight corpuscles may be shaken free from the atom. As these collisions take place in or beyond the negative glow they must be assigned to negatively charged atoms which, starting at the cathode, have acquired a high velocity by fall through the dark space—it should be noted that the ordinary speed of the molecule determined by temperature is utterly negligible compared with the speed which may be attained in the electric field. Some of these negative particles, by the loss of one or more corpuscles in the region of the negative glow, may become neutral or positively charged, the whole bundle of rays, moving from cathode to anode, some positive, some negative, the rest neutral, constituting the *retrograde* rays. It is, then, to the collision of the retrograde rays with neutral molecules that the multiply-charged atoms are regarded as owing their origin.

Again, there is the question of the mode of arrangement of the negative and positive charges in the neutral molecule. Do the component atoms hold a preponderance of charge of one sign? Can hydrochloric acid, for example, be represented diagrammatically as $\overset{+}{\text{H}} \overset{-}{\text{Cl}}$? Some of the phenomena of positive rays seem to lead to a different conclusion. Thus, though charged carbon atoms are present in the canal-ray beam, the particle $\text{C}++++$ has never been observed. The observations rather suggest the presence of neutral doublets and the diagrammatic representation of hydrochloric acid as $\overset{+-}{\text{H}} \overset{+-}{\text{Cl}}$. In agreement with this view is the fact that dis-

sociation of gases is often unattended by abnormal electrical conductivity. Nickel carbonyl, which dissociates at about 70°C., possesses, in the dissociated condition, very little conductivity. The flame of burning sulphur is stated by Bloch not to conduct below 400°C. Conduction at much higher temperatures, such as in a Bunsen flame fed with a salt, may result from an effect analogous to the emission of negative corpuscles from hot metals: the negative ions in the flame are certainly free corpuscles.

THE WORK OF OTHER OBSERVERS.

§ 9. *The Doppler Effect in Canal Rays.*—Stark's first Paper recording the observation of the Doppler effect in canal rays appeared in 1905. When the spectroscope was set so as to receive light from the beam in the direction of motion of the particles, the lines due to the gas were found to be doubled. Viewing normal to the beam the lines appeared as usual. The theory is expressed in the equation

**The
Doppler
Effect.**

$$d\lambda = \lambda_n - \lambda_p = \lambda_n \cdot \frac{v}{c}, \quad . \quad . \quad . \quad . \quad . \quad (v)$$

where λ_n , λ_p represent the wave-lengths when examined normal and parallel to the beam respectively, v denoting the velocity of the light-emitting particles, c the velocity of light. The illumination is too feeble for visual measurement. A four-prism spectrograph was employed, three to five hours' exposure being required. To secure steadiness of conditions in the discharge tube a 3,000-volt battery was used. The displaced lines showed a sharp edge on the side of the violet, gradually fading away on the red side. The change of wave-length was observed in line spectra, $d\lambda/\lambda$ having the same value for all lines of a series. Band spectra do not show the Doppler effect.

Calculating v for hydrogen from equation (v), the value 5×10^7 cm./sec. was found. Equating eV to $\frac{1}{2}mv^2$, taking $e/m = 9.5 \times 10^3$, the value of the speed v works out at 6×10^7 cm./sec.—the agreement of the numbers is fairly satisfactory. Stark points out that the series lines also show the Zeeman effect, and concludes that the light is emitted by electronic vibration within the atom or molecule. He adopts the view that the Doppler effect is shown only by positively charged particles,

the light-emitters in line spectra being positive ions, whilst in band spectra they are neutral particles. Wien, on the other hand, has adduced reasons for supposing it is the neutral particles that are concerned. A third view also finds support, namely, that the effect occurs at the moment of combination of a positive particle with a corpuscle.

Later observations under the greater dispersion given by the diffraction grating have shown that the displaced lines in hydrogen are doubled. Paschen attributed the constituents to the hydrogen atom and molecule respectively. This seems to be borne out by the measurements of Gehrcke and Reichenheim.

The results thus far attained by this method are somewhat disappointing. Owing to the necessity of long photographic exposure secondary batteries have to be employed across the discharge tube, and generally the voltages have been no greater than 600 to 1,100 volts. The value of $d\lambda$ in the case of hydrogen, as the data above quoted show, was of the order 10 Angstrom units, whilst the highest dispersion obtained by the grating was 19 Angstrom units per millimetre on the photographic plate. The accuracy of measurement attainable was not very high. Moreover, as has been shown, interpretation of the phenomena presents great difficulties.

**Wien's
Work.**

§ 10. *The Work of Wien.*—By allowing a linear thermopile to traverse the length of the band resulting from the spreading out of a narrow beam of particles by means of a strong magnetic field, the resulting galvanometer deflections being read off, Wien was able to compare the energy from point to point of the band. Two strongly marked maxima were found—one at the position of the undeflected spot, the second due to a certain set of the deflected particles. With hydrogen the energy of the positively charged particles was found to be decidedly greater than that of the negative, though small compared with that of the undeflected and therefore neutral particles. In the case of oxygen, on the contrary, the energy of the negative particles exceeded that of the positive. This preponderance of negative ions in oxygen he attributes, however, to the effect of mercury vapour. By freezing the mercury out with liquid air the positive particles appeared in excess. This result is in harmony with an observation of Sir J. J. Thomson that in presence of excess of oxygen the parabolic bands of mercury disappear.

Under the conditions of Wien's experiments it appears that on arrival at the thermopile the neutral particles were, in the case of all the gases tried, in considerable excess, the number of charged particles being only about 10 per cent. of the whole number present. Prof. Wien has also made determinations of the mean free path of the positively charged and neutral particles.

§ 11. Hammer has made an interesting experimental determination of the speed of the positive rays. Using combined parallel magnetic and electric fields a parabolic band was obtained, and this was adjusted to pass over a small hole in the screen. A narrow bundle of homogeneous rays passes on, and is allowed to traverse in succession two electric fields at right-angles to the beam and to one another. The parallel plates forming the boundaries of these electric fields were connected in parallel to the same alternator giving a practically pure sine wave. In general an ellipse was observed on a phosphorescent screen beyond the fields. If the time of passage between the two fields was a multiple of the period of alternation the ellipse became a straight line. The velocity of the beam could thus be calculated in terms of the distance between the fields and the period of alternation. He found in the case of hydrogen $v=2.51 \times 10^8$ cm./sec; this led to the value of $e/m=10,040$ E.M. units.

**A Speed
Determination.**

§ 12. The investigation of positive rays has so far been confined in the hands of a few prominent physicists. The field is a difficult one on both the theoretical and experimental sides. We cannot record as yet the untangling of the mystery of positive electricity, but new light has been thrown on the internal history of the molecule, and that seems to be the direction in which one may look for further discoveries in the near future.

CHAPTER III.

RUTHERFORD'S WORK ON THE α -PARTICLE.

§ 1. In the era of electrical research which one may conveniently date as beginning with the discovery of X-rays, one investigation has been by common consent singled out as a supreme intellectual and experimental achievement—namely, Sir J. J. Thomson's "counting" experiment, culminating in the estimate of the value of the charge of the electron, or negative unit of electricity. This result was announced in 1903. A second outstanding piece of work is that selected for the subject of this chapter, and embodied in two memoirs presented to the Royal Society in 1908; the one is entitled "An Electrical Method of Counting the Number of α -Particles from Radioactive Substances"; the other, "The Charge and Nature of the α -Particle." We may now accept the α -particles emitted by radioactive bodies, amongst which radium itself occupies the place of first importance, as consisting of rapidly moving particles of *helium* carrying a charge of positive electricity. If we denote this charge by the symbol E , using e to denote the numerical value of the unit negative electric charge, then according to the above work of Prof. Ernest Rutherford we have $E=2e$. The positive particles emitted by different radioactive bodies differ only in the speed of ejection. In their passage through matter they smash up or ionise the molecules in their path. In doing so they lose kinetic energy, and at a certain minimum velocity their ionising action ceases. The distance traversed, or the "range" of action, increases with the velocity of initial projection. For example, in air at normal pressure the range of α -particles from radium emanation is 4.3 cm., whilst for the particles from radium C the range is 7 cm.

§ 2. The determination of E involved two operations. Firstly, the actual counting of the number of particles emitted in a given time by a particular sample of radioactive matter; and,

secondly, the direct determination of the charge carried by the same particles in the same time. The unique feature of Rutherford's work is the experimental method selected for the counting experiment; a method which was carried in his hands to a triumphantly successful conclusion.

It is well known that a screen of zinc sulphide when subjected to bombardment by a sample of radium shows scintillating points. This brilliant effect is plainly seen in the scintilloscope, and is now delightfully familiar. It was early observed that these scintillations were due to α -radiation, and not to β or γ -rays; and it was suggested that possibly there was one scintillation for every α -particle striking the zinc blende target. Rutherford's results establish this as a fact. In the scintillating point we have the visible effect of a single atom of matter, the helium atom impressed with the enormously high velocity of its projection from a radioactive body.

The identification of the α -particle with the helium atom (with positive charge) has been carried by Rutherford to a remarkably direct test. The Papers already quoted, in conjunction with earlier work, lead to the result that the α -particle has a mass 3.84 times that of a hydrogen atom. The atomic weight of helium is known to be 3.96. The agreement of these numbers might be considered sufficiently within the probable limits of experimental error to warrant the deduction that the α -particle is identical with the helium atom. The direct experimental proof by Prof. Rutherford is in itself a further notable achievement. It will be found described in the "Philosophical Magazine" for February, 1909.

The determination of E. § 3. We will now proceed to consider the essential details of the crucial experiments referred to.

(1) *The Charge of the α -Particle.*—The determination of E consists in the measurement of the ratio

$$\frac{\text{total charge carried by a stream of } \alpha\text{-particles}}{\text{number of particles in the stream}}$$

The Counting Experiment.

Let us take first the method of determination of the denominator—that is, the "counting" experiment. The detectability of the α -particle lies in the very great ionising power it possesses. It is estimated that in its passage through a gas 46,000 pairs of ions are produced. Imagine these ions to be

produced in the gas between a pair of parallel metal plates maintained at a steady difference of potential. The ions of one sign would be swept by the field into the plate of opposite sign. Thus, if one plate is insulated its charge would be instantly altered by $46,000 e$ for each α -particle shot between the plates, where e denotes the ionic charge. This amount lies just on the verge of detection by a sensitive Dolezalek electrometer. To enhance the effect a magnifying device was employed. Townsend has shown that the production of a spark by an electric field is due to the rapid generation of fresh ions which is caused by the collision with neutral molecules of the ions already present in the gas, and which, moving along the lines of the field, acquire the requisite amount of kinetic energy. For P.D.s much below the sparking value only the negative ions are effective; but very near to the sparking P.D. the positive ions come into play, and likewise generate fresh ions. If, then, an

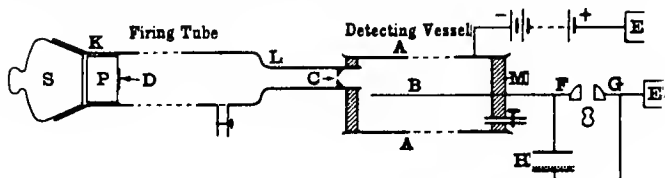


FIG. 10.—THE COUNTING EXPERIMENT.

α -particle be fired into the gas exposed to an electric field somewhat below the sparking value, each of the ions formed may in its turn generate fresh ions, multiplying in that proportion therefore the charge swept into each plate bounding the field. Such was the plan adopted by Rutherford. Each ion generated by the α -particle generated several thousands in its passage through the field.

Fig. 10 shows the apparatus employed. The radioactive preparation is placed in a very thin layer about 1 sq. cm. in area at D, centrally on the end of a hollow iron tube, P, which can slide along the interior of a glass tube, KL, 2.5 cm. in diameter and some 4 metres in length, one end of which is fitted with a diaphragm containing at its centre C a hole of known size, about 1.5 mm. diameter, whilst the other end is closed by a ground glass stopper S. This tube we may call

the *firing tube*. Connected to this tube, to the right of C, is a brass cylinder AA, closed by the ebonite stopper M, through which tightly passes a central wire B. The aperture at C is closed by a thin mica plate, which completely prevents the passage of gas between the chambers AA and KL. We may call AA the *detecting vessel*. The outer brass tube AA is connected to the negative pole of a secondary battery, the positive of which is earthed. The inner wire B is connected to one pair (represented by F) of the quadrants of a Dolezalek electrometer, the other pair being earthed.

Consider now the action in the detecting vessel and its connections. The contained gas (preferably helium, owing to the lower sparking potential and its freedom from natural disturbances which are found to occur when air is used) is at a pressure of a few centimetres of mercury. Let the two pairs of quadrants of the electrometer be metallically connected. The electrometer needle will be at its zero position. Now remove the connection. Since between A and B is the electrical field produced by the battery, there will, even though the field is small, be a slight current through the gas from A to B. When the battery E.M.F. approaches the sparking P.D., this current will be much greater as already indicated. Thus the quadrants F will be charged up, and the needle will steadily move away from zero. By now placing in parallel with the quadrants a radioactive leak, consisting of a layer of a radioactive substance spread over the lower of a pair of plates, H, the upper one of which is insulated and in connection with F, this charge will produce a current in the ionised gas between the plates of H, tending to reduce F and G to the same potential. The needle will thus after a time acquire a position of equilibrium which can be conveniently controlled by the adjustment of H. If now an α -particle pass through the mica window covering C into the detection vessel, the sudden increase of current from A to B will cause a ballistic throw of the electrometer needle, which will afterwards speedily resume its former position.

Consider, in the next place, the action in the firing chamber. A certain number of particles per second are flying off from the preparation at D. The average fraction that passes through the aperture at C may be calculated in terms of the distance between D and C, and the area of C. The actual

number entering the detection vessel may be varied by altering the activity of the preparation at D, and by adjusting the distance between D and C, a magnet being used to draw the iron cylinder P along the firing chamber. Rutherford arranged that the number of particles entering the detection vessel should be on the average about three or four per minute, at which rate the superposition of the effects of two successive particles is avoided, and the ballistic throws can be counted with certainty. By this means, then, the number of particles leaving a radioactive preparation in one second could be accurately determined. The preliminary tests to determine the best conditions for accuracy, such, for instance, as the best dimensions of the chambers to employ, are here passed over. In order to avoid stoppage of α -particles between D and C the firing chamber was exhausted to a charcoal vacuum. The stopping power of the thin mica film across C was found and allowed for. The actual preparation employed at D was radium C, the α -particles of which escape with the same velocity. The amount of RaC is estimated by comparison with a standard sample of radium in radioactive equilibrium, whence the result can be finally expressed in terms of the number of α -particles emitted in one second by 1 gramme of radium in radioactive equilibrium. The number expelled from the RaC in 1 gramme of radium was found to be 3.4×10^{10} per second. There are three other α -ray products which each emit the same number of α -particles. The total number of α -particles expelled per second from 1 gramme of radium in radio-active equilibrium is therefore 13.6×10^{10} .

[More recently, in place of the quadrant, the string electrometer has been used. This consists essentially of a thin silvered quartz fibre stretched between a pair of parallel plates kept at a fixed P.D. If the fibre receives a charge, it is deflected towards one of the plates. The movement can be recorded photographically on a rotating cylinder carrying a film. The fibre has a very short period—less than a thousandth of a second—and its movement is deadbeat. One end of the fibre is connected to one of the electrodes in the detecting chamber, the other end through a comparatively low resistance to earth. The entrance of an α -particle thus causes the fibre to receive an electric charge, which deflects the fibre, being then rapidly disposed of to earth. The phenomenon is recorded in a very short fraction

of a second and the fibre is ready to deal with another particle. It is possible to record as many as 1,000 α -particles per second with certainty. No final results by the method are as yet available.]

Total charge. There remains now the determination of the numerator, or the total charge of positive electricity carried by the stream of α -particles from the same RaC preparation; or, as in fact was the case, from a preparation of RaC whose strength is obtained by comparison with the standard sample of radium in precisely the same manner as in the counting experiment. The method of trapping the α -particles and of measuring their aggregate charge is one that had already been adopted with success by many workers, in the case of β and cathode as

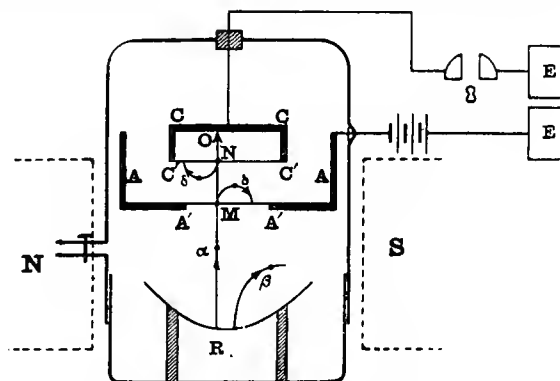


FIG. 11.—CHARGE OF THE α -PARTICLE.

well as α -particles. A very brief outline only of this measurement will here be given. The cup R (see Fig. 11) is coated on its interior surface with a thin layer of the radioactive preparation. The thick metal box CC facing R is connected with one pair of quadrants of an electrometer, the other pair being earthed. R and CC are enclosed in a vessel in which a charcoal vacuum is produced. α - and β -particles leave R, and the latter are turned aside by the magnetic field between the poles N and S of a magnet. A calculable proportion of the α -particles leaving R will strike CC and be absorbed completely, giving up their charges. The attached pair of quadrants thus becomes charged positively, and the needle will have a steadily

increasing deflection. The charge received is the product of the electrostatic capacity of CC (with its attached pair of quadrants) and the potential to which it has been raised.

The measurement would be extremely simple if the vacuum were perfect. The α -particles, however, ionise the residual gas, thereby making it a conductor. The charge of CC would therefore leak away. To eliminate this effect a second metal plate, AA, is placed below CC, the central portion A'A' being composed of a very thin sheet of aluminium. CC is likewise closed by a thin aluminium sheet, C'C'; α -particles starting from R thus reach CC after passing through the two thin plates A'A' and C'C', whose stopping power is comparatively small and calculable. To AA one pole of a battery of a few cells is attached, the other pole being to earth. If now the potential given to AA is negative with respect to CC, negative ions are carried into CCC'C', whose positive charge therefore accumulates less rapidly than before. If however the poles of the battery be reversed, the positive ions are swept into CC, which then gains positive electricity more rapidly than in absence of the battery. The mean rate of increase of the potential of CC in the two cases measures the rate of reception of the charges of the α -particles alone.

There is another disturbing element to be eliminated. When α -particles strike a metal, slow-moving β -rays, or δ -rays as they are termed, are generated. Those forming at M have to be prevented from striking C'C', whilst those generated at N have to be prevented from permanently leaving C'C'. The same magnet NS effects both these requirements. The diagram shows the slowly moving rays being bent into small circular orbits exactly as desired. (In Fig. 11, for diagrammatic simplicity, the orbits of the β and δ -rays are shown in the plane of the paper. The acceleration impressed on any particle is, of course, in reality perpendicular to the magnetic field.)

The charge nE carried by n particles is thus measured. The counting experiment has supplied the value of n . The resulting value of the charge of the α -particle as given by Rutherford is

$$E = 9.3 \times 10^{-10} \text{ E.S. units.}$$

The accuracy obtained appears to be high, of the order of 1 or 2 per cent. It is important to note that it is independent of

the assumed radium content of the standard sample in terms of which the strength of the RaC preparation was determined.

**Mass and
Nature of the
 α -Particle.**

(2) *Mass of the α -Particle.*—It had for a few years been suspected that the α -particle is a positively charged atom of helium. Helium is invariably found in radioactive minerals, and in these alone. It has furthermore been directly proved, first in 1903 by Ramsay and Soddy by aid of the spectroscope, that the radium emanation gives rise, in course of its transformation, to helium. Again, since the "counting experiment" gives the number of α -particles leaving a known quantity of radium in 1 second (13.6×10^{10} per gramme per second

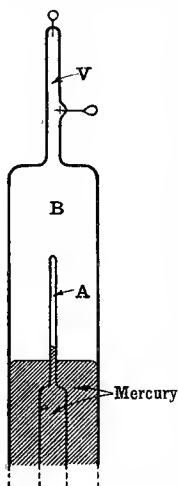


FIG. 12.—PROOF
THAT THE α -PAR-
TICLE IS AN ATOM
OF HELIUM.

for radium in radioactive equilibrium), and the number (2.72×10^{10}) of molecules per cubic centimetre of any gas at standard temperature and pressure is approximately known, the rate of evolution of helium from radium may be theoretically calculated if we assume each α -particle to be a (charged) helium atom. The calculated quantity is 158 cubic mm. per year, or 0.43 cubic mm. per day. The actual amount has been determined directly by Sir James Dewar, the pressure of helium generated in a known space in a given time by a known quantity of radium being measured by the McLeod gauge. In experiments extending over 1,000 hours the rate of evolution of helium worked out at 0.48 cubic mm. per day. The agreement is very remarkable.

However, the above evidence does not necessarily prove that helium actually consists of α -particles which have parted

**A Direct
Test.**

with their charge. As already stated, this point has been satisfactorily set at rest by Rutherford's Paper of 1909. The experiment is a very simple one. Radium emanation is enclosed in a very thin-walled glass tube, A (see Fig. 12), quite impervious to the emanation or to ordinary helium, but not to the rapidly moving α -particles. The surrounding vacuous space B may thus be examined spectroscopically for helium, utilising the capillary portion V of this space. The success of

the experiment was complete. The equilibrium quantity of emanation from 140 mg. of radium was compressed by a mercury column into the tube A, which had been drawn with walls only $\frac{1}{100}$ mm. thick, equivalent in stopping power to 2 cm. of air. B was initially exhausted to a charcoal vacuum. By raising the mercury column in B any gas present could be compressed into V, and the induction coil discharge made to pass. At first no trace of the helium line was to be seen; nor yet after 24 hours. In 48 hours the yellow helium line was visible; after four days the yellow and green lines of helium were bright, and after six days all the stronger lines of the helium spectrum were observed. Blank experiments were made to show that no helium was present in the glass or other parts of the apparatus. Helium gas was introduced into A, but no diffusion into B could be detected.

The material basis of the α -particle is thus demonstrated to be an atom of helium whose mass referred to that of the hydrogen atom is 3.96.

§ 4. *The Natural Unit of Electricity.*—The question of the exact value to be assigned to the electronic charge cannot yet be regarded as settled. The value which has thus far been commonly accepted is that given by Sir J. J. Thomson in 1903—namely, 3.4×10^{-10} E.S. units. H. A. Wilson arrived at the value 3.1×10^{-10} ; whilst Millikan, also utilising the formation of drops by the condensation of aqueous vapour on negative ions, gave the number 4.06×10^{-10} . In his later experiments Millikan improved the method, replacing the water drops by drops of oil, and thus eliminating the uncertainties connected with evaporation: these experiments gave the value $e = 4.90 \times 10^{-10}$. Townsend, by a distinct method, concluded that the smallest elementary ionic charge is about 3.0×10^{-10} . Boltwood's determination of the transformation constant of radium, combined with Rutherford's counting experiment, leads to $e = 4.1 \times 10^{-10}$. Perrin's estimate, from observations on Brownian particles, of the number of atoms in 1 gramme of hydrogen, leads to the value 4.1×10^{-10} .

The Value
of e .

Regener made observations on the α -particles emitted by polonium, counting with extreme care the number of scintillations produced on a zinc sulphide screen. This number was assumed to be equal to the number of α -particles emitted by

the polonium. Combining this with a determination of the total charge carried by these particles, the value 9.58×10^{-10} was arrived at for E . By assuming $E=2e$, Regener thus finds for e the value 4.79×10^{-10} . Rutherford has actually determined the number of scintillations produced by a radioactive sample, and at the same time the number of α -particles by the method of his "counting" experiment; and has discovered practically perfect agreement. For instance, in one experiment 294 scintillations were counted, this number proving to be 99 per cent. of the number given by the electrical method; in a second, involving 150 scintillations, the ratio was 96 per cent. This experimentally observed agreement adds weight to the value obtained by Regener for e .

Rutherford's experiments give $E=9.30 \times 10^{-10}$, and this number is evidently one to which much consideration should be accorded in a revision of the value to be assigned to e . He accepts the view that the charge e carried by the hydrogen atom in the electrolysis of water is the fundamental unit of electricity, and that, therefore, E must be some multiple of e , either two or three. From considerations based on Boltwood's experiments, referred to above, he fixes upon the multiple two, and thus assigns to e the value 4.65×10^{-10} .

Finally, there is Planck's estimate of e based on thermodynamical considerations applied to radiation data, which lead to the number 4.69×10^{-10} .

It will be seen that the later values are distinctly higher than those first found. More work perhaps requires to be done before a revised value can be confidently chosen.

CHAPTER IV.

CURIE'S WORK ON MAGNETISM.

1. The name of the late M. Pierre Curie is mainly associated with the discovery, in conjunction with Mme. Skłodowska Curie, of radium. Perhaps this fact has helped to obscure a long and careful series of investigations of an earlier date which we owe to M. Curie. This work owes its value to its suggestiveness in regard to the causes underlying the behaviour of magnetic substances as well as to the importance of the experimental results achieved. The appearance of Langevin's electronic theory of magnetism was a fitting sequel to Curie's labours on the experimental side. Curie's Paper, "The Magnetic Properties of Bodies," appears to have been offered to the Faculty of Sciences of Paris as a thesis for the doctorate in physical science. It was published in the "Annales de Chimie et de Physique" of 1895. The Paper appears in full in the edition of Curie's collected works compiled by the French Physical Society (1908).

The object of the present article is to set forth the results, to give some description of the methods employed, and to state the points of view impressed upon Curie in the course of his work.

2. Langevin has adopted a classification of bodies, as regards magnetic properties, which lends clearness to the subject and is in harmony with the laws established by Curie. In place of dividing bodies into diamagnetic and paramagnetic, according as the magnetic permeability is less or greater than unity, Langevin restricts the term paramagnetic to those bodies (invariably feebly magnetic) for which the susceptibility is independent of the strength of the magnetic field.

**Langevin's
Classification.**

Adopting, then, Langevin's nomenclature, substances may be divided into—

(1) Diamagnetic substances, in which the induced polarity is opposed to that of the inducing field.

(2) Paramagnetic substances, which are feebly magnetised in the same direction as the inducing field ; the susceptibility being independent of the field intensity, and (though there are now known to be exceptions to this rule) inversely proportional to the absolute temperature.

(3) Ferromagnetic bodies, magnetised in the same sense as class 2, but far more strongly, the susceptibility being a complicated function of the magnetic field and of temperature.

**Curie's
Work.**

3. Curie examined the properties of a number of bodies in each of these classes, over a range of magnetic force from 25 to 1,300 C.G.S., and over a temperature range from that of ordinary air to 1,350°C. The quantity in terms of which his numerical results are expressed is the susceptibility K , defined as the quotient of the magnetic moment per unit mass by the

magnetic field intensity, or $K = \frac{I_m}{H}$. This coefficient may be termed the *mass susceptibility*. It is found by dividing the susceptibility as usually understood in this country, the volume susceptibility, by the density of the substance.

**Measure-
ment of
Susceptibility.**

The method of measurement chosen was the determination of the force experienced by the specimen when placed in a non-uniform field, this force being towards stronger parts of the field where K is positive, towards weaker parts where K is negative. This method has the convenience that quite small samples may be employed.

**Diamagnetic
Bodies.**

The results, briefly outlined, were as follows : In the case of *diamagnetic substances* the susceptibility was found to be, in most cases, *independent of H and of temperature*. Bismuth, which is usually accepted as the most pronounced example of a diamagnetic body, is an exception to the above rule whilst in the solid state ; its susceptibility falls with rise of temperature up to the point of fusion, when it suddenly drops to one-25th of its value. Fused bismuth is actually the most feebly diamagnetic substance known. In the fused state the value of K for bismuth is strictly independent of temperature.

In most cases there is no change in K at the moment of fusion or with alteration to an allotropic form. In a few substances change of physical state does produce an effect. As a further instance, the change from white phosphorus to red is

attended by a fall in K amounting to 20 per cent. Antimony also, like bismuth, appears to be anomalous.

The *paramagnetic bodies* chosen were oxygen, palladium, air and ferrous sulphate. For all these the susceptibility was found to be *independent of H* , and *inversely proportional to the absolute temperature*. Glass and porcelain were also studied to permit of corrections being applied for the perturbing effects of the glass or porcelain bulbs used for holding the test samples. Glass is most often diamagnetic, but sometimes magnetic, at ordinary temperature, this evidently depending on the proportion of iron oxide in its composition. In the case where it is magnetic it becomes diamagnetic at high temperatures, the results being expressible by the formula $K = \frac{K'}{T} - A$. The same

Paramagnetic Bodies.

is true of the glazed Bayeux porcelain used in the high-temperature experiments.

Curie examined Wiedemann's and Plessner's observations, which show that $MnSO_4$ and $CoSO_4$ obey the above law, whilst for $NiSO_4$ the change in K is more rapid than according to the inverse temperature law.

The *ferromagnetic bodies* studied were soft iron, cast iron, magnetite (Fe_3O_4) and nickel. The results are expressed in two families of curves, the first connecting I and H , temperature constant; the second connecting I and T , H constant. For a certain range of temperature above the critical temperature, or temperature of magnetic transformation, each of these substances satisfies the two laws pertaining to the paramagnetic body: (1) I independent of H , and (2) $K \propto \frac{1}{T}$; the value of

Ferromagnetic Bodies.

K being then of the same order as for paramagnetic bodies. As the temperature falls there is continuity of passage from the paramagnetic state to the complicated ferromagnetic condition.

Curie's Analogy.

In the former stage the substance obeys the law $I = A \frac{H}{T}$, which is of the same form as the equation for a perfect gas—namely, density $= \frac{1}{R} \cdot \frac{p}{T}$, the density of the gas corresponding to intensity of magnetisation, the pressure p to magnetic force, A and $\frac{1}{R}$ being the respective constants. Just as the gas equation

breaks down in the region of the critical temperature, so does the paramagnetic formula fail near the temperature of magnetic transformation. The loss of simplicity in the law of variation of density with pressure and temperature is due to intermolecular action; the same may be true of the phenomenon of magnetisation. This analogy of Curie's was adopted and worked out in Langevin's theory.

Whilst, however, the ferromagnetic condition is shown to change continuously into the paramagnetic, there is no such continuity between paramagnetism and diamagnetism; and the conclusion is drawn that the diamagnetic and paramagnetic effects have distinctly different underlying causes.

Such is a brief *résumé* of the results of Curie's work. A more detailed account follows below.

Extrapolation of Curie's Law.

The interesting question occurs whether Curie's law for paramagnetic bodies holds down to extremely low temperatures.

The law $K \propto \frac{1}{T}$ would imply infinite susceptibility at absolute

zero. It might thus be expected that every paramagnetic body would pass into the ferromagnetic condition at a certain point down the temperature scale, its temperature of magnetic transformation; or, at all events, that at some ascertainable point the inverse law would cease to hold. Dewar and Fleming have shown ("Proc. R.S.", 1898) that for solid MnSO_4 the law holds down to -186°C .; and in the case of liquid oxygen the mass-susceptibility found at -186°C . agreed very closely with that deduced by extrapolation from the value for oxygen at ordinary temperatures. The density of liquid oxygen is 806 times that of the gas at 0°C . and 760 mm., whilst the temperature on the absolute scale is only one-third: the agreement of observed and calculated values is certainly striking. So far, then, as these measurements go there is no divergence from the paramagnetic condition to be recorded.

Theory of Measurement of K.

4. *The Determination of K.*—As already outlined, the method adopted by Curie for the measurement of the susceptibility was that of finding the pull experienced by a specimen of the substance when placed in a non-uniform magnetic field. The magnetic energy per unit volume of a body of permeability μ in a field of force \mathbf{H} is given by the expression $\frac{\mu \mathbf{H}^2}{8\pi}$. Assum-

ing the permeability of the surrounding medium to be unity, we have force on specimen = volume $\times \frac{d}{dx} \cdot \frac{\mu-1}{8\pi} \mathbf{H}^2$, in the direction of x . Denoting the volume susceptibility by k , since $\mu=1+4\pi$, we may write force = volume $\times \frac{d}{dx} \cdot \frac{K\mathbf{H}^2}{2} = vk\mathbf{H} \frac{d\mathbf{H}}{dx}$; or, employing the mass-susceptibility K , force = $MK\mathbf{H} \frac{d\mathbf{H}}{dx}$, M

being the mass of the specimen. In this simple expression K is assumed invariable with respect to intensity of field. \mathbf{H} denotes the actual magnetic field within the specimen. For diamagnetic and paramagnetic bodies demagnetising action is inappreciable. In the case of ferromagnetic bodies, for a sufficiently large ratio of length to lateral dimensions, the same remarks hold true; but in general, for bodies of this class, this demagnetising effect, and the variation of K with \mathbf{H} , as well as a perturbing couple due to the long axis of the specimen not exactly coinciding with the direction of the magnetic field, have to be investigated and allowed for.

To find K , then, the value of the product $\mathbf{H} \frac{d\mathbf{H}}{dx}$ must be known over the whole range of fields used. This involved a series of preliminary measurements. \mathbf{H} was found by the effect on a standardised ballistic galvanometer of reversal of a small bobbin placed at any required point in the field. $\frac{d\mathbf{H}}{dx}$ was similarly

found by the aid of a flat search coil set with its plane perpendicular to the field and suddenly moved through a short interval of $\frac{1}{2}$ mm. to $1\frac{1}{2}$ mm. in the direction of the field; or, still better, by a like motion of the coil when set perpendicular to the above-mentioned plane. (These give the same throw, since $\frac{d\mathbf{H}_y}{dx} = \frac{d\mathbf{H}_x}{dy}$, \mathbf{H}_x denoting field parallel to axis of x .)

The latter was the plan ingeniously adopted, as the results are thereby freed from the disturbing effects of small accidental variations in \mathbf{H}_x , the resultant magnetic field. Values of \mathbf{H} and of $\frac{d\mathbf{H}}{dx}$, and thus of $\mathbf{H} \frac{d\mathbf{H}}{dx}$, were obtained at different points in the field. The point where the product $\mathbf{H} \frac{d\mathbf{H}}{dx}$ is a maximum

was chosen for the position of the specimen, slight error of setting being thus rendered inappreciable. The character of the results is shown by the curves of Fig. 13.

These quantities were determined for varying magnetising currents in the coils of the electromagnet, which was of the Faraday form. The values were plotted as ordinates against currents as abscissæ, and in the actual experiments the values of $H \frac{dH}{dx}$ were deduced from the readings of the current, care being taken always to vary the current cyclically between the

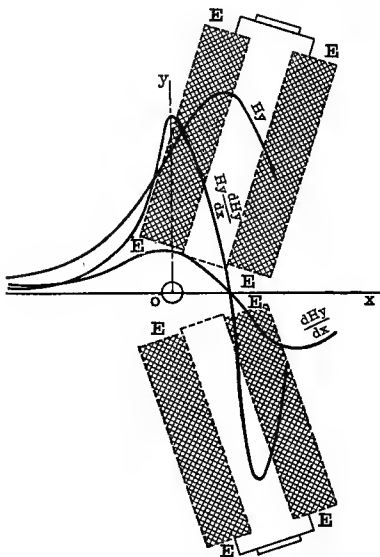


FIG. 13.

same extreme limits positive and negative (+8 to -8 amperes), and to note whether the field was due to a falling current or a rising one. Indefiniteness due to hysteresis was thus eliminated.

Effect of Impurity.

5. The purity of the specimen was carefully examined. Iron if present as a salt has only a small effect; but insignificant quantities of iron in the metallic form, or as oxide or sulphide, can profoundly modify the behaviour of a paramagnetic, and

still more of a diamagnetic body. Its presence was evidenced either by marked hysteresis effects or by the complicated character of the IH curve, as contrasted with the straight line passing through the origin, which all pure paramagnetic or diamagnetic substances give. Some quantitative experiments on the effects of such impurity were made, using paste impregnated with known amounts of powdered metallic iron. The results show that 1 part of iron to 100,000 of water on the average just annuls the diamagnetism, and gives rise to enormous hysteresis effects; 1 in 200,000 reduces the mean dia-

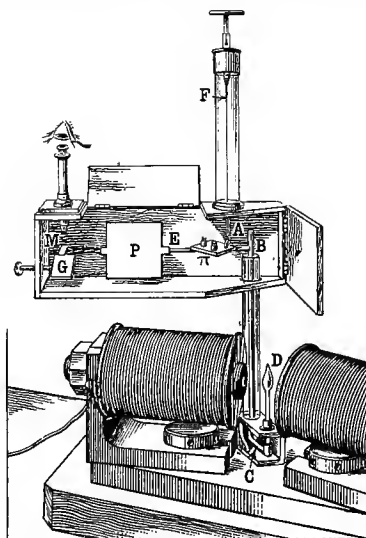


FIG. 14.—THE TORSION BALANCE.

magnetic susceptibility to one-half, and still gives large hysteresis effects; 1 in a million causes a mean error in K of 10 per cent., hysteresis is no longer sensible, but the IH line is distinctly curved, being convex towards the axis of H . Laboratory dust is ferriferous, but its influence is different from that of pure iron; the effect, due probably to the sesquioxide, is to displace the IH curve so that it no longer passes through the origin.

6. The pull on the specimen was measured by a torsion balance. This is illustrated in Fig. 14. The torsion wire FA carries

The Torsion Balance.

a copper framework, EABC, on one side of which is supported the bulb D containing the specimen, whilst on the opposite side there is attached a large vertical vane, P, of aluminium, serving to damp the vibrations of the system; and beyond is a fine rod supporting the micrometer scale M. The balance arm is horizontally adjusted for varying masses of specimens by weights placed in the horizontal pan π . The form of the right-hand arm of the suspension may be seen in Figs. 14 and 15; this design served to secure stability in the moving system, and to remove the balance arm out of the range of influence of the stray magnetic field. On either side of P, and only a few millimetres from it, are fixed two similar parallel plates; the movements of the balance are thus rendered dead beat. The whole instrument is enclosed in a wooden case lined with tinfoil, all metal parts being connected together and to earth in order to avoid forces due to possible electrification.

The displacement of the bulb D (denoted by a in Fig. 15) on switching on the magnetic field was deduced from that in the micrometer M. With the aid of a reading microscope the movement of D could be measured to within a thousandth of a millimetre. The position of the specimen was carefully adjusted to the same point in the magnetic field in each experiment.

Several torsion wires were used. Couples per unit displacement in the proportions 1:3.6:42.8 were thus available as required.

The Electric Furnace.

7. *Method of Heating.*—An electric furnace was employed (Fig. 15). Over a porcelain tube, $pppp$, 12 cm. in height, closed at the upper end, a platinum wire, 0.7 mm. to 0.9 mm. in diameter, was wound in a double spiral, the wire being firmly fixed in position by kaolin put over as a paste and baked hard. A larger porcelain tube, PP, went over this, the intervening space being filled with calcined magnesia or kaolin. To keep the interior temperature more uniform the tube was wound with more turns of wire per unit length below than above. 1,500 watts sufficed to maintain the highest temperature (1,350°C.) employed. By hand regulation of a rheostat in the heating circuit the temperature of the interior could be maintained constant to $\frac{1}{10}$ °C.

The specimen, in small pieces or as a fine wire, is supported in the bulb *a* (of Fig. 15), which is constructed either of glass or porcelain or platinum. The bulb is supported on the stem *tt* of glass or porcelain, this in turn fitting into the metal frame TT, which is attached to the moving system of the torsion balance. The electromagnet and the balance were protected from the heat of the furnace by the water-jacket ABC, through which

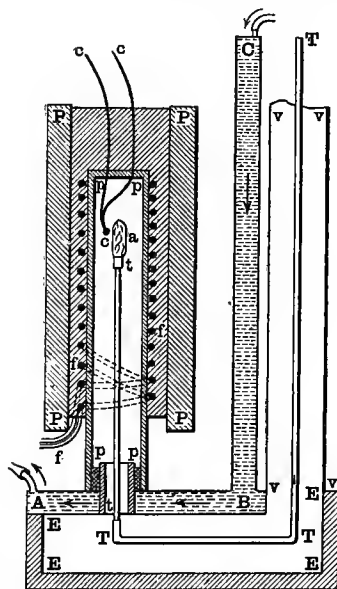


FIG. 15.—THE ELECTRIC FURNACE.

water continually circulated. The wooden box *EE* and the tube *vv* served to protect the stem *tt* against disturbing air currents.

Temperatures were measured with a Le Chatelier thermocouple, standardised by Baudin and Delaunay thermometers, and the use of a series of standard melting and boiling points.

CHAPTER V.

CURIE'S WORK ON MAGNETISM (*continued*).

1. In the last chapter an account was given of the experimental arrangements adopted by M. Curie for carrying out his research on the magnetic properties of bodies over a wide range of field strength and of temperature. It is proposed here to deal with the actual data which his observations supplied, and to consider the extent to which the laws proposed by Curie are true. Curie concluded his memoir by pointing out what has proved a fruitful analogy—namely, between the laws of passage from the liquid to the gaseous state and from the ferromagnetic to the paramagnetic condition. This analogy led to Langevin's electronic theory of diamagnetism and paramagnetism, followed by Weiss's attempt at a working theory of the ferromagnetic condition. The chapter concludes with an account of these later developments.

2. *Diamagnetic Bodies*.—The substances tested by Curie were as follows : Water, rock salt, quartz, KCl, K_2SO_4 , KNO_3 , S, Se, Te, Br, I, P, Sb, Bi. Water was very carefully studied, with a view to a reliable absolute determination of the susceptibility K ; the value of K for other bodies was deduced with reference to that of water as the standard. The remarkable behaviour of bismuth was the subject of special attention. In every case K was found to be independent of H . With the exception of perhaps three, all gave a value of K independent of temperature and of physical state.

**Diamagnetic
Substances.**

3. *Water* was examined in the liquid state, and by enclosure in sealed glass tubes a range of temperature from $20^{\circ}C.$ to $199^{\circ}C.$ was covered. Measurements were made with the bulb full, then with the bulb empty ; the correction on account of the material of the bulb and of the air was eliminated by difference. This procedure was common to all the torsion-balance experiments. In the case of water the correction was a large one,

Water.

amounting to 4 per cent. The value adopted for K was -0.79×10^{-6} . (Quincke found 0.815; and Du Bois, using Quincke's method, 0.837.) Curie concludes that its variation with temperature over the range taken is certainly within the limits of experimental error—namely, 1 per cent.

Crystalline quartz has the same susceptibility in all directions.

Sulphur is a good example of a substance where the invariability of K persists through changes of allotropic form and through passage from the solid to the liquid state.

Phosphorus shows a distinct drop (about 20 per cent.) in K on passage from the white to the red variety. There is no change at fusion. Each variety shows invariability with respect to temperature.

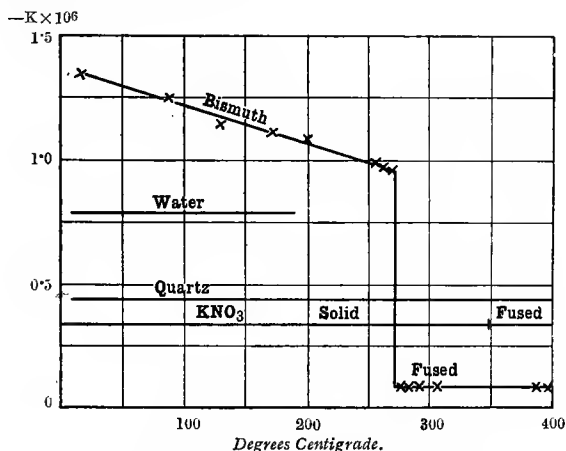


FIG. 16.—DIAMAGNETIC SUSCEPTIBILITY.

Bismuth.

Bismuth in the solid state furnishes an example of a definite law of variation of K with temperature. The law is the linear one. At fusion there is a sudden drop to one-twenty-fifth of its value. Whereas in the solid state this metal possesses the highest value of diamagnetic susceptibility known—namely, -1.35×10^{-6} at 20°C ., in the liquid state, it possesses the smallest—namely, -0.038×10^{-6} . Between 20°C . and 273°C . the results are expressed by the formula,

$$10^6 K_t = -1.35[1 - 0.00115(t - 20)].$$

It is safe to conclude that Curie's law of K independent of T represents an important simple natural fact. But whilst the law holds exactly (within the limits of experimental error) for many diamagnetic bodies, it is seen that it does *not* hold for others. Typical results are shown in Fig. 16.

4. *Paramagnetic Bodies.*—Oxygen, palladium, air, FeSO_4 in aqueous solution, glass and porcelain were experimentally studied. Plessner's and Wiedemann's results for paramagnetic salts were examined and discussed, and shown to bear a different interpretation from that of the authors.

Paramagnetic Bodies.

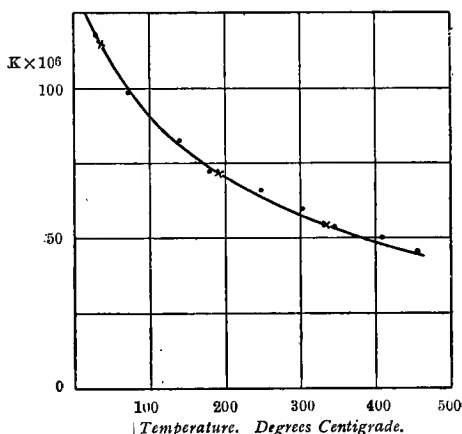


FIG. 17.—SUSCEPTIBILITY OF OXYGEN.

The first four bodies above enumerated were found to have a susceptibility independent of strength of magnetic field, and also to satisfy Curie's second law $K = \frac{\text{constant}}{\text{abs. temp}}$. Glass and porcelain are composite substances, and were studied purely for the purpose of determining the correction to be applied for the bulbs containing the test specimens.

Oxygen was enclosed in a glass bulb under pressures up to 18 atmospheres. K was found to be independent of pressure. The range of temperature was from 20°C. to 450°C. The results are expressed in the curve of Fig. 17. The product KT , which has been called the "Curie constant,"

is $33,700 \times 10^{-6}$. Thus, $K_{20} = 115 \times 10^{-6}$. The susceptibility of *air* was shown to be calculable on the assumption that it is due solely to the oxygen present, the nitrogen acting merely as a diluent; the product $KT = 7,830 \times 10^{-6}$.

A perfectly pure sample of *palladium* was studied up to $1,370^\circ\text{C}$., and gave $KT = 1.520 \times 10^{-6}$.

For *ferrous sulphate* in aqueous solution the value calculated is for the salt only, that of water, taken as -0.79×10^{-6} at all temperatures, being allowed for. The result is $KT = 24,200 \times 10^{-6}$.

In all these cases K is seen to be numerically very much greater than in the case of any diamagnetic body.

Wiedemann and Plessner had carried out measurements of the susceptibility of magnetic salts, and had suggested an equation of linear form, $K_t = K_0 (1 - at)$. Curie showed that for MnSO_4 and CoSO_4 their results are really expressible in terms of a hyperbolic law, or $K \propto \frac{1}{T}$. In the case of NiSO_4 the susceptibility changes more rapidly than according to the inverse temperature law.

It will be seen that Curie's law applies to all the chemically pure substances tried by him, and to the results of the other observers quoted, with one exception, namely, NiSO_4 . Once more it may be inferred, then, that some simple natural process is in evidence, though later experiments quoted below confirm the conclusion that there are paramagnetic bodies to which Curie's law does not apply.

Ferromagnetic Bodies.

4. *Ferromagnetic Bodies*.—A very careful series of measurements was made upon soft iron over the full range of temperature and field at command. Nickel and magnetite were studied at temperatures above that of magnetic transformation. Cast iron was also examined.

Soft Iron.

The results for *soft iron* are represented as two families of curves, the first connecting intensity of magnetisation and magnetic force at constant temperature, the second connecting intensity and temperature for constant field.

Fig. 18 shows the former set of curves. To eliminate complication due to hysteresis, prominent for small fields though vanishingly small in the higher fields used, the curves represent the "stable magnetisation" of the specimen. This curve,

which may be attained by the aid of mechanical vibrations or of an auxiliary alternating magnetic field, lies between the ascending and descending limbs of the hysteresis loop, and passes through the origin.

It will be seen that for low fields the curves for different temperatures have a portion in common. Consider, for example, the curves for 20°C. and 601°C. As far as an intensity (magnetic moment per unit *mass*) of 130 the curves are practically identical. At this point the curve for 601°C. rises more slowly, proceeding to a saturation value much smaller than at 20°C. Each curve is regarded for convenience as consisting of three portions. Taking, for example, the 601°C.

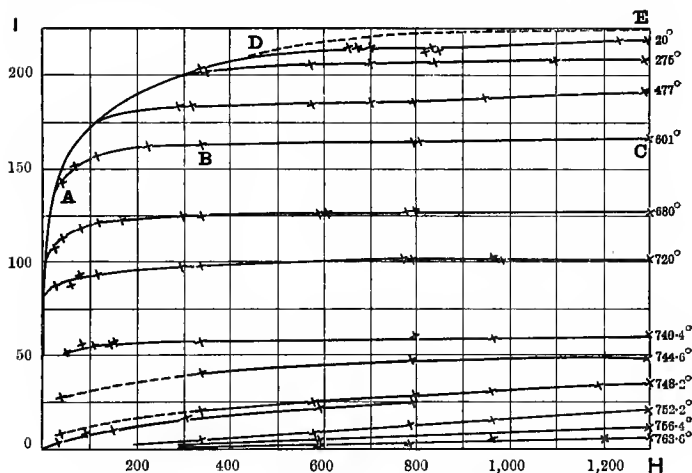


FIG. 18.— I AND H (TEMPERATURE CONSTANT) FOR IRON.

curve, the first portion OA is very steep, the third portion BC is practically a straight line parallel to the axis of H , whilst the middle portion AB serves to connect the other two. Curie imagined a limiting curve, OADE, to which these curves would approximate more and more nearly the lower the temperature—in other words, the curve for absolute zero. As the temperature rises, the first portion (corresponding to OA) becomes shorter, likewise the third portion, until at 752°C. and upwards the curves become straight lines passing through the origin ;

the curves for temperatures near the point of magnetic transformation are shown to a larger scale in Fig. 19. The family of curves serves to show the continuity of passage, with rise of temperature, from the ferromagnetic to the paramagnetic state.

Curves connecting I and temperature are shown in Fig. 20 for fields of 25, 300 and 1,000 C.G.S. respectively. As H increases by equal steps the curves get closer and closer together, approaching a limiting value corresponding to infinite field strength. For low fields the maximum magnetisation may be attained at a temperature considerably above ordinary air temperature. In the strongest fields there is from the first a steady fall of I with increase of temperature. The curves gradually close in to one another as the temperature of magnetic transformation is approached. Curie has pointed out the vagueness that exists in the definition of this temperature. For each value of H the I, T curve descends very rapidly as the

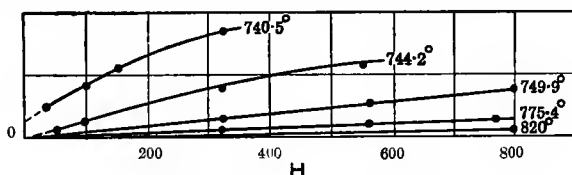


FIG. 19.— I AND H FOR IRON.

critical point is approached, the slope attaining its maximum steepness at a certain temperature, an inflection therefore existing in the curve at this point. But this temperature of inflection depends upon the particular field strength used, varying, in the case of soft iron, between $740^{\circ}\text{C}.$ for weak fields and $760^{\circ}\text{C}.$ for very strong fields. Curie proposed to adopt the mean of these limiting temperatures as the temperature of magnetic transformation. The results at still higher temperatures are shown, with ordinates magnified 1,000 times, to the right in Fig. 20. Only one curve, that for $H=1,000$, is given, since beyond the temperature of magnetic transformation the susceptibility is independent of the field strength. It will be seen that I continues to fall very rapidly long after that temperature is exceeded. At $930^{\circ}\text{C}.$ (point A of Fig. 20) the slope

suddenly diminishes ; and between $930^{\circ}\text{C}.$ and $1,280^{\circ}\text{C}.$ soft iron behaves as a paramagnetic body, satisfying the law $K \propto \frac{1}{T}$.

This second series of curves again shows how rise of temperature is attended by the continuous passage of soft iron from the ferromagnetic to the paramagnetic condition.

The behaviour of soft iron shows, however, many complications. These are brought out more clearly in Fig. 21, where the logarithm of K is plotted against the logarithm of the absolute temperature. In addition to the point of inflection occurring at a (the point of magnetic transformation), another occurs at b and another at c . From c to d the curve becomes a straight line, with a negative slope of unity, which means that over this portion the law of inverse temperature holds. At $1,280^{\circ}\text{C}.$

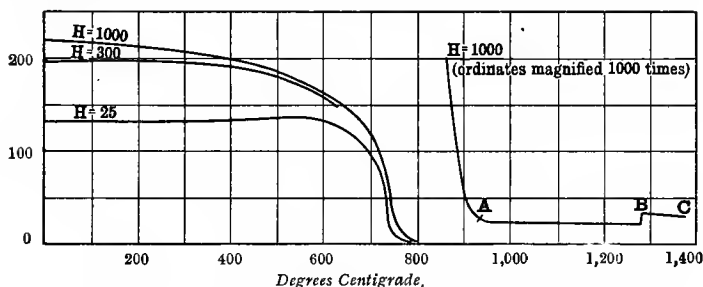


FIG. 20.—INTENSITY OF MAGNETISM AND TEMPERATURE (H CONSTANT).

the susceptibility suddenly rises by half its value to e , after which it apparently resumes parallelism with cd . Curie interpreted the portion bc as indicating a steady change of the iron to an allotropic variety, the change being complete at c ; and regarded this result as confirmatory of Osmond's theory of α , β , and γ iron.

Magnetite was carefully studied, the specimen consisting of the natural octahedral crystals. The temperature of magnetic transformation is $535^{\circ}\text{C}.$ From $550^{\circ}\text{C}.$ upwards K is independent of H , but it is not until $850^{\circ}\text{C}.$ is reached that K varies inversely as the absolute temperature ; this relation continues to hold as far as $1,360^{\circ}\text{C}.$, the highest temperature employed, the Curie constant being $KT = 28,000 \times 10^{-6}$.

Magnetite.

Cast iron was investigated with a view to showing the effect of carbon on the magnetic properties of iron. Between 850°C . and $1,267^{\circ}\text{C}$. it behaves as a paramagnetic body, with the product $KT = 38,500 \times 10^{-6}$. The effect of the carbon appears to be to lower the temperature at which the stage *cd* sets in (see Fig. 21).

The results for nickel, and also for oxygen, ferrous sulphate, and palladium, are included in Fig. 21. The slope of the right-hand portion of the curves of the ferromagnetic group coincides

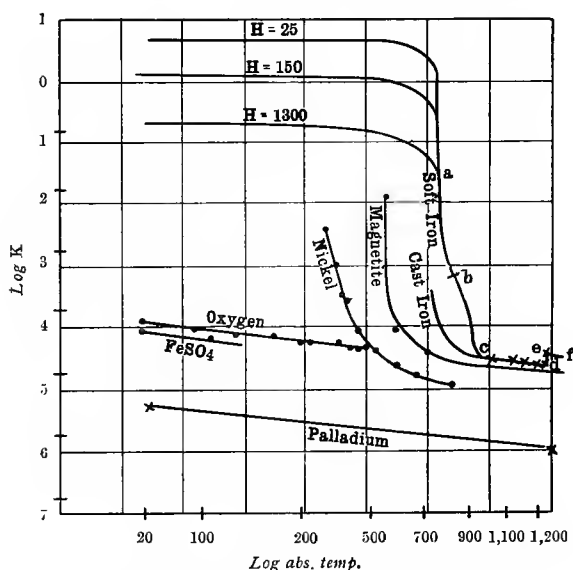


FIG. 21.—SUSCEPTIBILITY AND TEMPERATURE.

with that of the paramagnetic bodies; at a certain temperature the former class passes into the latter, with constants of the same order as for oxygen, &c.

Curie's Analogy.

5. *Curie's Analogy.*—The fact that a liquid can pass continuously into the gaseous state under variation of pressure and temperature is a very familiar one. The magnetic behaviour of iron as field strength and temperature vary is

strikingly similar. This resemblance was brought out by Curie by means of sets of curves relating to the two classes of phenomena. These are reproduced in Figs. 22 and 23.

Fig. 22 represents Amagat's results for carbon dioxide, Fig. 23 Curie's results for soft iron. At a sufficiently elevated temperature, on the one hand, the simple law of the gas, $\text{density} = \frac{1}{R} \cdot \frac{p}{T}$, is attained; whilst on the other the simple law of the paramagnetic body, $I = A \cdot \frac{H}{T}$, comes into operation.

6. *Later Experimental Data.*—It is seen that Curie showed that the law of invariability of susceptibility with temperature

Later Experimental Data.

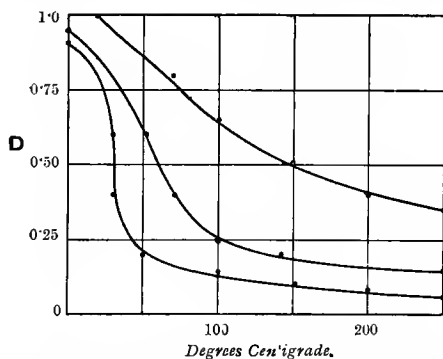


FIG. 22.—DENSITY AND TEMPERATURE (p CONSTANT).

does not apply in every case of a diamagnetic body. In regard to paramagnetic bodies, the only exception to the inverse temperature law encountered appeared to be NiSO_4 . Subsequent work by other observers establishes the existence of other exceptions. Weiss and Kamerlingh Onnes, in the course of a research on magnetisation down to very low temperatures ("Journal de Physique," July, 1910) have shown that in the case of the metals manganese, vanadium, and chromium the susceptibility is practically invariable from ordinary temperatures down to that of liquid hydrogen. Their results for manganese are especially interesting. The metal was prepared in the pure state by the electrolysis of MnCl_2 . The grey powder

Manganese.

obtained was compressed into a compact rod. On examination it revealed the constant susceptibility and absence of hysteresis of the paramagnetic body. Melted in an electric furnace in a vessel of magnesia, in an atmosphere of hydrogen, a solid rod was produced which on cooling behaved as a ferromagnetic body. A hysteresis loop was obtained, showing a saturation value of intensity of magnetisation one-hundredth part of that of pure iron, with a coercive force of 670 C.G.S.—*i.e.*, about six times greater than that of permanent magnet steel. This is reminiscent of Hopkinson's nickel steel with its two states, the paramagnetic and the ferromagnetic, existing at the same temperature. Honda and Du Bois have also recently discovered

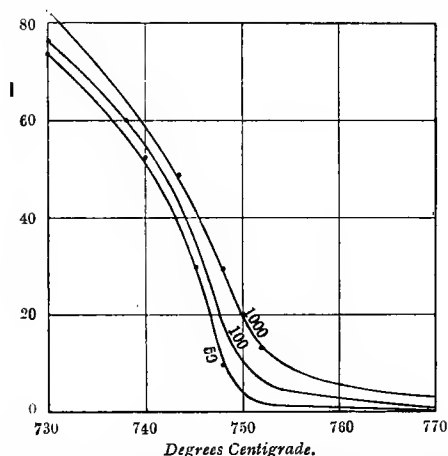


FIG. 23.—INTENSITY AND TEMPERATURE (H CONSTANT).

several cases where the paramagnetic susceptibility is independent of temperature, or even increases with rise of temperature.

Weiss has shown that in the case of all the ferromagnetic bodies above the critical temperature θ the law of variation of susceptibility with the temperature is more accurately expressed by the formula $K(T - \theta) = \text{constant}$: a formula which he deduces from the theory of the molecular field.

Weiss has closely examined the law of variation of intensity of magnetisation of ferromagnetic atoms with temperature, and

its dependence in the case of salts and other compounds on the mode of chemical combination. In the case of magnetite above the Curie point, if the reciprocal of the intensity be plotted against temperature the curve is made up of five straight portions, the transition from one piece to the next being sometimes quite sharp, sometimes by continuous change of slope over a small range of temperature. The corresponding intensities are in the proportions of 4 : 5 : 6 : 8 : 10. To explain these results he advances the hypothesis that the magnetic moment of the atom or molecule changes by abrupt steps, the smallest of which constitutes a natural unit of magnetic moment, the *magneton*, the same for all ferromagnetic and paramagnetic bodies. An examination of the changes of magnetic moment with difference of chemical linkage, based on the data of Pascal and of Liebknecht and Wills, leads Weiss to the same conclusion. The experimental data point to the quantity 1123.5 as the unit per gramme-atom; dividing this by Perrin's value 68.5×10^{22} for the number of atoms per gramme-atom the value 16.4×10^{-22} is obtained for the *magneton* itself. In the atoms of Fe, Ni and Co in the uncombined state the number of magnetons at very low temperatures is 11, 3 and 9 respectively. For copper sulphate in aqueous solution $n=10$; whilst if in ammoniacal solution $n=6$. The double iodide of potassium and mercury, $2KI \cdot HgI_2$, is interesting in that the component elements are diamagnetic, whilst the compound is paramagnetic ($n=9$).

7. *Langevin's Theory*.—Ampere's molecular current in a circuit of zero resistance is realised in the electronic orbit. A single molecule contains as many elementary current circuits as there are electrons in motion. If these are so arranged that the resultant magnetic moment is nil, we have the *diamagnetic* molecule. When the resulting magnetic moment is finite, we may have two cases: first, when the mutual magnetic influence of these molecules is inappreciable—the body is then *paramagnetic*; second, when each molecule is sensibly influenced by its neighbours—this constitutes the *ferromagnetic* state. In accordance with Curie's analogy, Langevin treats the first two classes of bodies as consisting of molecules, as it were, in gaseous condition. If the body is diamagnetic, no orientating action of the external magnetic field will result, and there will

**Langevin's
Theory of
Diamagnetic
and Paramag-
netic Bodies.**

be no change of the aggregate motion. The ulterior encounters between the molecules will take place as before, and no change of temperature can result. Conversely, no change of temperature will modify the diamagnetic property of the body.

Langevin comments to the effect that all the electrons in the molecule contribute to the action; and the motion of these, as is shown by the constancy of the spectral lines, does not depend upon temperature. It may be questioned how far this is true, and to what extent alteration of temperature may alter molecular constitution, and so affect the value of the susceptibility, even though the diamagnetic property persists.

In regard to the *diamagnetic* molecule, Langevin's calculations, worked out on the basis of a circular electronic orbit, give for the increase of magnetic moment produced by an external field the value $\Delta M = -\frac{He^2S}{4\pi m}$, whilst $M = \frac{eS}{T}$; where e =charge of electron, S =area of orbit, T =period of revolution, m =mass of electron. Thus

$$\frac{\Delta M}{M} = \frac{HT}{4\pi} \cdot \frac{e}{m} < 10^{-9}H.$$

Since no value of H as high as 10^5 can be obtained in practice, this means $\frac{\Delta M}{M} < 10^{-4}$, which accounts for the smallness of the diamagnetic susceptibility. When the molecule is paramagnetic this diamagnetic modification must be regarded as still present, and superposed on the paramagnetic effect. It is so small, however, as to be completely masked by the latter.

When the molecule is *paramagnetic* the effect of an impressed magnetic field is to tend to set the molecules with their magnetic axes parallel to the field. This tendency is opposed by the thermic agitation and by collisions which tend to re-establish the state of primitive disorder. There results a statistical equilibrium, for which the resultant intensity of magnetisation is a function of the magnetic field divided by the kinetic energy of agitation of the molecule. This application of the magnetic field to a paramagnetic body is analogous to the creation of a gravitational field within a closed region occupied by a gas. In the latter case the effect is to cause the molecules in the lower part of the containing vessel to have greater velo-

cities than those at the top. This means an inequality of temperature. To restore the original temperature throughout heat has to be abstracted. There results, too, a redistribution of molecules, the density increasing from below upwards. The corresponding lowering of the centre of gravity is inversely proportional to the absolute temperature.

The redistribution of axes in the magnetic problem corresponds to the redistribution of density in the gravitational one, and Langevin applies the Maxwell-Boltzmann law to its solution. The result is expressed in the equation

$$\frac{I}{I_0} = \frac{\cosh a}{\sinh a} - \frac{1}{a}, \quad \dots \dots \dots (1)$$

where $a = \frac{I_0 H}{RT}$, I_0 denotes the numerical sum of the magnetic moments of all the molecules in 1 gram-molecule, I the actual intensity in a field H , and RT = twice the kinetic energy per degree of freedom of the molecule multiplied by the number of molecules in one gram-molecule. The equation (1) represents a magnetisation increasing from zero as H increases, and finally taking up a saturation value corresponding to complete alignment of the molecules. For all values of H that can be obtained in practice, however, I is proportional to H —that is, the susceptibility is constant. For small values of H/T equation (1) reduces to $I/I_0 = \frac{a}{3}$, or $I/H = \frac{I_0^2}{3RT}$. That is, the susceptibility is inversely as the absolute temperature; which is Curie's law for the paramagnetic body.

8. M. Pierre Weiss in 1906 expounded a theory of the ferromagnetic body in which the liquid analogy is worked out. Each molecule has its "sphere of molecular action," and is subjected to a field in the same direction as I and proportional to it. This field, called the "molecular field," is estimated at the enormous figure of 6×10^6 C.G.S. It corresponds to the Laplacean internal pressure.

**The Work of
P. Weiss.**

This field is regarded as the only force which constrains the direction of the axis of the molecule—apart from that the substance would behave as a gas. The laws of the paramagnetic body are assumed to apply to ferromagnetic substances, the

total field being the external applied field plus the "molecular field," just as the laws of the gaseous state have been applied to account for the properties of a liquid, the total pressure being regarded as the resultant of the externally applied pressure and the "internal pressure." Denoting the molecular field by H_m , Weiss writes $H_m = NI$, where N is a constant. At the Curie point the relation $\theta = CN/D$ holds, where θ denotes the critical temperature, C the Curie constant in the paramagnetic state above the critical temperature, D the density. From this relation N can be calculated, and so H_m . For iron

$$N = \frac{756 + 273}{0.034 \times 7.86} = 3850, \text{ whence } H_m = 3850 \times 1700 = 6.54 \times 10^6$$

C.G.S., at the ordinary atmospheric temperature.

The theory leads to the notion of *corresponding magnetic states*, defined by the equations,

$$\frac{T}{\theta} = \frac{3}{a} \frac{I_m}{I_{m_0}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (a)$$

and
$$\frac{I_m}{I_{m_0}} = \coth a - \frac{1}{a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (b)$$

where I_m denotes the intensity of magnetisation per gram-molecule at absolute temperature T , I_{m_0} the corresponding quantity at absolute zero. The equation (b) represents the generalised Langevin formulæ. From these formulæ it follows

that the curve connecting $\frac{I_m}{I_{m_0}}$ and T/θ should be the same for all ferromagnetic bodies. The actual curves obtained from experimental data show that this result holds for magnetite extremely well over the upper portion of the range of temperature, but not at the temperature of liquid hydrogen. In the cases of Fe, Ni, and Co there is greater divergence. The alloy Fe_2Ni furnishes a case where the agreement is perfect over the whole range of temperature. The discrepancies led Weiss to the view that Langevin's assumptions were too simple, and that it was necessary to postulate the variability of magnetic moment of the elementary atom. Trial showed that the saturation values, at very low temperatures, of the magnetic moment per gramme-atom of the elements Fe, Ni, and Co stand in the simple relation 11 : 3 : 9. Hence the hypothesis

of the *magneton*, a natural unit magnet of invariable magnetic moment. Further data bearing on this hypothesis have been quoted in § 6 above. Reference may also be made here to an interesting Paper by Ashworth ("Phil. Mag.," 1912) showing identity of the values $\frac{I}{I_0}$ for iron, nickel and cobalt in corresponding magnetic states, the intensities in that case being residual intensities.

It will be seen that Curie's suggestions as to the continuity of the ferro- and paramagnetic states, and of the liquid-vapour analogy, have led Weiss to results of a fundamental character. Out of his work has arisen the idea of the *magneton*, playing a part in magnetic phenomena corresponding to that taken by the electron in electrical phenomena. This view bids fair to take a secure place in electrical theory in the near future.

CHAPTER VI.

THE AURORA.

1. The phenomenon of the Aurora, in many of its superficial aspects, is a matter of almost daily experience in high northern and southern latitudes. While in our own latitudes the "northern lights" are neither frequent nor brilliant, they are a never-failing source of interest and an unceasing object of inquiry. The journal of an arctic or antarctic expedition is never dull reading. As regards its inner mechanism the aurora is far less communicative. Schuster in 1889 proved that the diurnal variation of the earth's magnetism has its origin *outside* the earth's surface, and drew the natural conclusion that it is due to electric currents circulating in the upper regions of our atmosphere. De la Rive had previously shown an experiment in which the electric discharge in an exhausted bulb containing a magnet pole was supposed to reproduce some of the appearances of aurora. This, however, and the later experiments of Lemström, do little more than suggest that the aurora is an electrical phenomenon, and susceptible to a magnetic field.

**Theories of
Mechanism.**

The recent enormous accessions to our knowledge in regard to the electric discharge in gases have naturally paved the way to a more thorough elucidation of the subject. Below are considered two recent investigations whose aim is to reproduce experimentally the phenomena actually observed on our globe. The first series of experiments is due to Prof. BIRKELAND, and is devised to support his theory that perturbations of the earth's magnetic field, and polar auroras, are both effects arising from the same cause—namely, the precipitation on the earth of streams of electric corpuscles shot out from the sun's surface, especially in the region of sunspots.

The second series of experiments is due to the able French scientist P. VILLARD. By means of a beam of cathode rays moving in a magnetic field some of the chief auroral charac-

teristics are strikingly reproduced. The source of the cathode beams which are thus regarded as causing the aurora is held to be terrestrial, and not of solar or cosmic origin.

Auroral Phenomena.

2. Before proceeding to an account of these two "working models" it will be well to recall briefly the main facts of the aurora. As seen in high latitudes the characteristic *form* taken is that of a luminous arc, the highest point of which is in or very near the magnetic meridian. Within this arch of light the sky is comparatively dark, the lower boundary of the arc being fairly sharp. From the upper side streamers radiate into the sky, constituting as it were spokes of light, whose bases rest on the auroral arc, their upper ends fading to extinction, or sometimes converging to form the "corona." Of course the effects are often more complex, a confusion of vertical rays, arcs, scrolls, bands, draperies and luminous patches, baffling description.

The Spectrum.

As regards *colour*, a rosy tint is often seen at the base of the auroral arc. Higher up the prevailing colour is a whitish yellow, passing into a green light at the highest points of the streamers. Examined by the spectroscope some nine lines are visible, including the characteristic yellowish-green line which the smallest spectroscope will show. For long these remained unidentifiable with any known spectral lines. More recently, by photography, the number has been increased to upwards of a hundred, mostly in the ultra-violet region; and most of them have been identified with the lines emitted by the most volatile constituents of atmospheric air, unliquifiable at the temperature of liquid hydrogen. The rosy tint of the auroral arc appears to be mainly due to neon, and the characteristic yellowish-green line to krypton.

Movement, often very rapid, is seen to occur. Sometimes it appears to be one of rotation about the earth's magnetic axis, the bases of the streamers gliding as it were along the auroral arc. Or the effect observed is one of displacement of the streamers in the direction of their length ('dance' of the rays).

The Upper Atmosphere.

Estimates of the *height* of the aurora are rather uncertain. As seen in high latitudes, the auroral arc is to be reckoned in tens of miles above the ground, though sometimes it is undoubtedly much lower, being seen projected against the background of neighbouring mountains. As seen in our own latitudes the

height is very much greater, say, a hundred or several hundreds of miles. In this connection it is important to note that the composition of the atmosphere would be expected to vary greatly with height. Each constituent gas may be pictured as forming a separate atmosphere of its own, the density at higher elevations falling off more gradually the lighter the gas. Whilst at the earth's surface nitrogen and oxygen predominate, hydrogen constituting only some 1 part in 100,000, at a height of 50 miles nitrogen and oxygen will be practically absent; the hydrogen greatly preponderating, with helium and neon present in large proportion. Pickering has actually observed the hydrogen and helium lines in the spectrum of a meteoric stone entering the limits of our atmosphere.

Quite recently Störmer has made precise measurements of the parallax of the beams and arches of the aurora. He did this by simultaneous photography of the aurora and of the brightest stars appearing through, at stations in Norway a few kilometres apart connected by telephone. Out of 150 well-determined altitudes the lowest cases occurred at an altitude of about 40 km. The upper limit was at 260 km. Störmer is also making cinematographic studies of the aurora, which are likely to be of great value.

In *extent*, auroras may be local, or they may cover practically the whole of our globe at once. The former are observed in the polar regions. As regards the latter, the visual phenomena have been observed even at places within 20 deg. of latitude on either side of the equator, and there is little doubt that the large displays occur simultaneously in both hemispheres. It follows that the *frequency* of display increases as one leaves the equator. But this does not go on without limit; a zone of maximum frequency is reached, approximately circular, and situated some 15 deg. from the magnetic pole. Another curve, not quite coinciding with the line of maximum frequency, has been drawn, such that at places on this line the aurora appears just as frequently to the south (speaking of arctic regions) as to the north. Within this zone, and therefore in strictly polar regions, the frequency of occurrence and the brilliancy of the phenomenon fall off considerably, and, moreover, it most often appears to the south of the observer.

The effects are in the daytime totally masked by the sun-

light. They appear at their maximum a few hours after sunset, the intensity at an equal interval before sunrise being incomparably feebler.

The apparent *connection with cirrus clouds* has been often observed. After dawn succeeding an auroral display the cloud forms seen will often be strikingly like those of the aurora. Acute observers have been doubtful whether they were viewing glowing cirrus clouds or aurora.

Villard's Experiments.

3. VILLARD, in 1906, published an account of some remarkable experiments. Many authors have suggested that auroral phenomena are due to electric discharges similar to the cathode discharge in a vacuum tube, and this view is no doubt generally held. In the experiments cited it has been sought, by the action on a beam of cathode rays of a magnetic field similar to the terrestrial magnetic field, to reproduce many of the characteristic effects of structure and movement in the aurora. Photographic records were made of the path of the cathodic beam, some of which are reproduced opposite. A thin parallel beam of rays was obtained by aid of a flat cathode, in front of and close to which was placed a mica plate with a minute hole in it. The gas employed in the bulb was oxygen.

If the beam is shot at right angles to a *uniform* magnetic field, the path of the rays, as is well known, is a circle of radius inversely proportional to the field strength. Fig. 24 shows the result obtained for several successive strengths of field.

When the beam is shot obliquely in the uniform field, the resultant path is a spiral of constant pitch, whose axis is parallel to the field. Fig. 25 represents this case.

Experiments were next made in the field between two equal magnetic poles of opposite sign. The field was produced by means of two straight electromagnets set in line with one another, the rods being long in comparison with the distance apart of their adjacent ends. Consider a beam of cathode-ray particles shot in the equatorial plane of this field. As the particles get nearer to the axis of the field they pass into a region where the magnetic force is stronger, and vice versa. The result will be a path as shown in Fig. 26. Fig. 27 is a reproduction of Villard's photograph for this case.

To take a step further: consider a beam of particles whose velocity contains a component parallel to the axis of the field



FIG. 24.—UNIFORM FIELD. CATHODE RAYS PROJECTED NORMALLY. (VILLARD.)



FIG. 25 — UNIFORM FIELD. CATHODE RAYS PROJECTED OBLIQUELY. (VILLARD.)

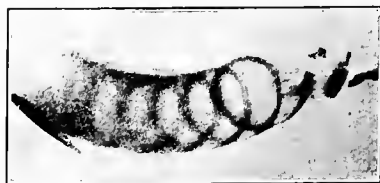


FIG. 27.—PHOTOGRAPH OF RAYS IN FIELD AS SKETCHED IN FIG. 26. (VILLARD.)

last described. The particles should now start on some spiral path whose axial direction makes an angle with the meridional planes of the field. But there is a further factor to take into account. Movement parallel to the axis of the field means passage into the stronger field near a pole. This causes the pitch of the spiral to diminish, and ultimately results in a reversal of path. The beam spirals to the other pole, again to suffer a reversal of direction, and so on. Thus a zigzag will be described over a surface whose axis is that of the field. To an observer situated in the field between the poles, and looking

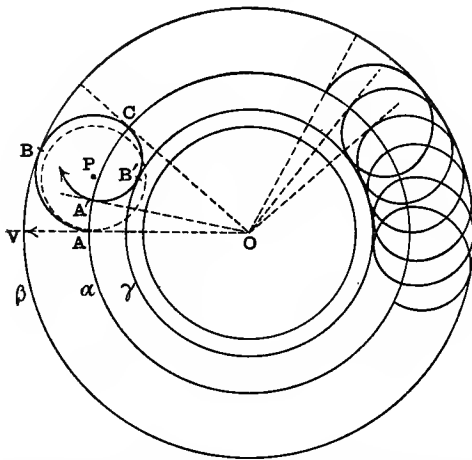


FIG. 26.—FIELD BETWEEN TWO POLES. CATHODE RAYS PROJECTED IN EQUATORIAL PLANE. (DIAGRAMMATIC REPRESENTATION.)

in the direction of the north pole, the cathode particles would describe spirals in the clockwise direction, the resulting zigzag line being such as to carry the particles from west to east. The apparatus, and the effect which should be produced, are shown diagrammatically in the drawing of Fig. 28; whilst an actual photograph of the discharge is shown reproduced in Fig. 29. The beam has its origin in the top right-hand corner of Fig. 28, and in the top left-hand corner of Fig. 29.

On these experiments Villard bases his explanation of the aurora. Imagine the bulb and field of Fig. 28 expanded to the

size of the earth, and compare the luminous effect with that of the classical aurora. The consecutive elements of the zigzag cathodic path represent luminous streamers converging to the poles, but stopping at a distance from them and resting, as it were, on arcs with black interior. This is shown in Fig. 30, where the photograph has been taken from a different point. At either arc, and some distance from it, two adjacent beams, one incoming, the other outgoing, will overlap and so give an increased brightness. If the "step" of the zigzag is greater than the breadth of the beam, the classical fantail will result; if less, then distinct overlapping ensues, causing the appearance of a drapery. A change in the strength of the field, or of the speed of the rays, will alter the step, and so cause an apparent sliding

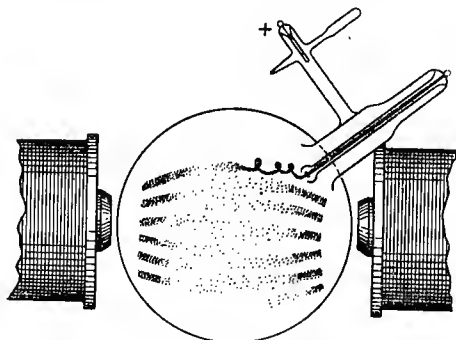


FIG. 28.—FIELD BETWEEN TWO POLES CATHODE RAYS PROJECTED OBLIQUELY. (DIAGRAMMATIC REPRESENTATION.)

movement of the bases of the beams on the auroral arc. A change in the point of convergence of the field will cause a movement of the arc up and down, just as in the so-called "dance" of the rays. The first kind of movement could be produced in the vacuum bulb by alteration of the strength of the magnet; the second by the approach of a piece of soft iron near to a pole.

The path in the earth's magnetic field should be described from west to east, and should, therefore, fade in intensity as one travels east, dying away after a certain fraction of a rotation is completed. Thus, the aurora should be seen most distinctly soon after sunset, afterwards fading away as



FIG. 29.—PHOTOGRAPH OF ZIGZAG PATH OF RAYS IN MAGNETIC FIELD.
(VILLARD.)



FIG. 30.—VIEW OF RAYS FROM DIFFERENT POINT. (VILLARD.)

the place of observation is carried by the earth's rotation further and further east of the meridian containing the sun ; which agrees with observation.

M. Villard goes further, and regards his experiments as pointing to the terrestrial origin of the cathodic streams. Were they of solar origin, he considers that the extent of the phenomenon should be a surface whose radius is that of the earth's orbit, as the place of origin must lie on the trajectory of the particles. Whilst regarding the source of the rays as uncertain, he suggests the possibility of its being in the masses of electrified ice particles constituting cirrus. The undoubted influence of the sun is regarded as a trigger effect : possibly the cirrus clouds may act as great secondary cathodes, excited by the bombardment of solar corpuscles ; or the negative electricity may be discharged by the incidence of the ultra-violet rays, since Buisson has shown that ice crystals negatively charged show the photo-electric effect. The cathode beam would be shot perpendicularly to the surface of the cloud—*i.e.*, nearly vertically—and thus obliquely to the earth's lines of force. The path described would be that of the model as shown in Figs. 28 and 29, only on the gigantic scale in which the turning points are the earth's north and south magnetic poles.

4. Prof. K. BIRKELAND, in 1896, propounded the solar corpuscular theory enunciated above. Since that time he has engaged in three Arctic expeditions for the purpose of acquiring data respecting the value of the perturbations in the magnetic elements, and their relation to auroras. At the same time he has conducted experiments on the effects produced by a beam of cathode rays shot off in the direction of a magnetised sphere or "terrella" enclosed in the discharge bulb. The terrella was mounted on a universal joint so that the relative positions of the earth (represented by the terrella) and the place of origin in the sun's surface (represented by the cathode) could be reproduced for different times of day and different periods of the year. The P.D. across the tube was 3,000 volts, obtained from a Thury direct-current dynamo. The terrella was magnetised by currents going up to 33 amperes.

**Birkeland's
Experiments.**

Though Birkeland has not succeeded in embracing phenomena over the whole globe in his theory, he claims to have explained elementary magnetic storms quite satisfactorily.

The negative equatorial storm, for instance, which is attended by a decrease in the horizontal component at or near the equator, he explains as due to a circular stream of cathode rays encircling the magnetic equator. Fig. 31 is from a photograph of the effect as shown on the terrella. In Fig. 32 is shown the production of luminous rings over the polar regions. These he regards as corresponding to the auroral zones.

Störmer's Models.

He has been assisted by Prof. Störmer, who has calculated the possible trajectories of electrified particles shot from the sun in the direction of the earth. One class of rays, he shows, would strike the earth at nearly normal incidence; whilst a second class should approach the earth and then recede, after grazing the earth tangentially. The circular ring of Fig. 31 is interpreted as the envelope of rays of the latter kind. The results are shown by means of wire models, an example of which is shown in Fig. 33, representing the case of rays shot out above the equatorial plane of the earth, rays that actually terminate on the earth's surface being, however, purposely omitted.

Source of Energy.

5. In comparing different explanations of aurora, and magnetic storms or magnetic variations in general, it is very important to bear in mind the energy point of view. Birkeland appears to ascribe the source of energy to the sun, and proceeds to form an estimate in horse-power of the requisite solar radiation, and to speculate on its relation in amount to the heat and light emitted, on the basis of radioactive theories.

Lord Kelvin, over half a century ago, argued the impossibility of a solar origin for the energy, by showing that the sun would have to emit as much radiation in the course of the few hours of a storm as it does normally in the course of several months. The possibility of a limited beam of cathode rays originating in a very small area of the sun's surface—namely, at a sunspot—seemed to offer a simple way out of the energy difficulty. After all, the extra draft of energy called for might be comparatively small. Schuster, however, has pointed out—by reasoning from which there seems no escape—that Lord Kelvin's *reductio ad absurdum* still applies. Schuster inclines to the view that the source of the energy is to be found in the kinetic energy of rotation of the earth, the mode of transformation being probably by the movement of masses of air across the earth's lines of force, whereby electromotive forces are

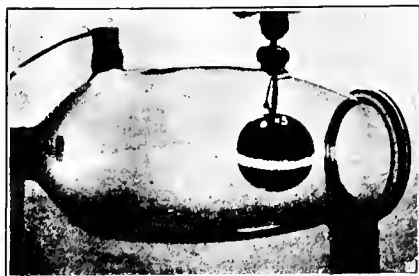


FIG. 31.—TERRELLA IN VACUUM TUBE. (BIRKELAND.)



FIG. 32.—LUMINOUS RING ON TERRELLA, CORRESPONDING TO POLAR AURORAL ZONES. (BIRKELAND)

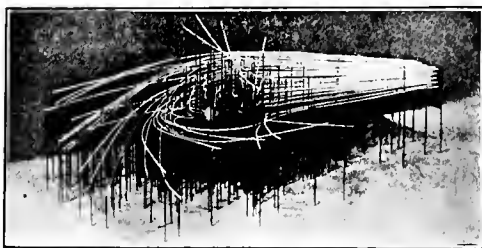


FIG. 33.—WIRE MODEL OF TRAJECTORIES OF SOLAR CORPUSCLES IN MAGNETIC FIELD OF THE EARTH. (STÖRMER)

induced. Electrical energy being the product of volts and amperes, electric corpuscles or ultra-violet radiation from the sun would play the rôle of increasing the conductivity of the paths of the induced currents.

Much of interest has yet to be learnt concerning the connection between air movements and atmospheric electrical phenomena, and more definite knowledge of the laws of these movements may do much to clear up the mystery still attaching to the Auroral branch of Meteorology.

CHAPTER VII.

BROWNIAN MOVEMENTS.

1. If a liquid containing very fine particles—for example, water to which a small proportion of milk is added, or a mixture of dilute sodium hyposulphite and dilute acid—is examined under the high powers of the microscope, the particles are seen to be in incessant to-and-fro motion. If lateral illumination is employed, particles far smaller than those detectable by ordinary illumination manifest themselves, standing out, by the light they scatter, against a dark background, just like stars in the night sky. The lively dance of bright spots, often in brilliant colours when sunlight or the light of the arc is used, is a fascinating one to watch. In 1827 the English botanist BROWN called attention to this phenomenon. For a long time the subject was left unheeded, being regarded by physicists as carrying no special significance. In 1888 GOUY published the results of experiments which clearly showed the character of these movements to be independent of external vibration, of convection currents arising from inequalities of temperature in the liquid, or of the intensity of illumination employed. The movement goes on always, to a less extent the more viscous the liquid. He therefore put forward the hypothesis that we have here an agitation of the same nature as that postulated in the kinetic theory of matter.

2. The kinetic theory begins with the atomic conception of matter, adding the hypothesis of the incessant movement of the constituent molecules of a body. In the case of gases the theory is capable of being mathematically followed out in many of its consequences, as has been done especially by Clausius and Maxwell. One fundamental theorem is that of the equi-partition of energy among the molecules of a gas, independently of the nature of the molecule. If m denotes the mass of any molecule, v its velocity, then $\frac{1}{2}mv^2$, or w , the mean kinetic energy of translation of the molecule at any par-

**The Kinetic
Theory.**

ticular temperature, is a universal constant. It follows that all gases contain the same number of molecules, n , per unit volume, at the same temperature and pressure; or, in other words, that the number N of molecules in the gram-molecule of any gas is the same. The number of molecules in 2 grams of hydrogen and in 36.5 grams of hydrochloric acid gas is the same, being of the order of, say, 60×10^{22} . The pressure exerted by a gas is the resultant effect of the molecular bombardment of any surface exposed to the gas. It is thence deducible that $pv = RT$, and that $w = \frac{3R}{2N} \cdot T = \alpha \cdot T$, R having a constant value, 83.2×10^6 , for the gram-molecule. Thus, if w (or α) is known, N is known; or vice versâ.

The electronic charge e is also connected with N , since Ne is the charge conveyed by 1 gram of hydrogen in the electrolysis of water—namely, 96,540 ampere-seconds or 29×10^{13} electrostatic units.

The kinetic theory connects such apparently diverse magnitudes in gases as the pressure, the coefficient of diffusion, the thermal conductivity, and the viscosity.

When applied to liquids the kinetic theory, owing to the complexity introduced by inter-molecular actions, has not found accurate mathematical expression. Van't Hoff, noting that the values of osmotic pressure obtained by Pfeffer depended only on the number of molecules of dissolved salt per unit volume, and not on the nature of the salt, and that the pressure was the same as that produced by the same number of molecules in the gaseous condition, concluded that the mean kinetic energy of each one of the molecules concerned was equal to that of a gas molecule. Going a stage further, the conclusion seems inevitable that not merely a few distinguishable molecules, but that *all* the molecules of a liquid, solvent as well as solute, should be regarded as possessing this same quantity, w , of kinetic energy of translation. Where the liquid is electrically conducting, each ion is to be regarded as a molecule in the sense of possessing the same kinetic energy.

The kinetic theory has even been applied to the free electrons which are postulated as existing, like a very light gas, in the interstices of a metal. Supposing these electrons to possess the molecular kinetic energy w , dependent on the

temperature of the metal, but independent of its chemical nature, the ratio of the electrical and thermal conductivities and the temperature variation of that ratio may be deduced. The calculated values show striking agreement with experiment. Lorentz, starting from this conception of free electrons, has deduced an expression for the heat radiation from a metal. Equating to the data of experiment, a value for w has been thence obtained agreeing very well with the value adopted for the ordinary gas molecule.

3. The *Brownian movement*, as we have seen, raised the question as to whether the kinetic theory could be regarded as applying to particles consisting of assemblages of molecules so large as to be actually visible. Maxwell, writing on the kinetic theory, refers to the state of perfect repose which, even under the highest power of the microscope, appears to exist in a body. The Brownian movement forms an exception to this generality. Does it fall in the category of kinetic heat movement?

**Einstein's
Displacement
Formula.**

Since Gouy's arresting memoir of 1888 much has been done in the direction of an answer in the affirmative. In 1906 Einstein, and independently Smoluchowski, showed how to express the mean displacement of such a particle in terms of N . Einstein's formula is

$$\xi^2 = \tau \cdot \frac{RT}{N} \cdot \frac{1}{3\pi a \zeta} \quad \dots \dots \dots (1)$$

where ξ represents the displacement in any given direction in a time τ , a denotes the radius of the particle assumed spherical, ζ the coefficient of viscosity of the surrounding medium. This equation contains the assumption that the particle possesses the mean kinetic energy of translation w , also that the frictional resistance to its movement through the medium is given by Stokes' celebrated formula $F = 6\pi a \zeta v$, where v is the velocity of the particle with respect to the medium.

In 1908 and 1909 JEAN PERRIN made an extremely important series of experimental contributions to the subject. It is the main object of this article to outline the methods and the results of this remarkable research. His experiments fall in two classes. In the first place he conceived the idea of testing whether, in a liquid medium in which are suspended granules

**The Work
of Perrin.**

of uniform size large enough to be visible, these particles follow the law of concentration that holds for a gas under the influence of gravity. In an enclosure at constant temperature the density of a gas is greatest at the bottom of the vessel, decreasing in geometrical progression as the height increases in arithmetical progression. The granules will attain this distribution if their mean energy of translation is constant. Denoting the value of this energy by W , the equation

$$\frac{2}{3}W \log \frac{m_0}{m} = \varphi(\Delta - d)gh. \quad \dots \quad (2)$$

holds; m_0 and m denoting the number of granules per cubic centimetre at two points between which the difference of level is h , φ the volume of each granule, Δ and d the density of the granular material and of the liquid respectively, g the acceleration due to gravity.

Microscope construction has now been brought to a high degree of perfection, and with the aid of lateral illumination particles of ultramicroscopic magnitude can be rendered visible. Perrin realised the possibility thus presented of subjecting the above equation (2) to the test of direct experiment. He prepared an emulsion containing granules of practically uniform size, and succeeded in showing that when allowed time—generally a few hours—to attain the steady state of distribution, the density of distribution of the granules decreases from the bottom of the vessel upwards, and this according to the exponential law. But whilst in the case of our atmosphere half density would be attained at a height of some 6 km., in the case of these emulsions the half concentration occurs with a rise of one-hundredth of a millimetre. The size of the granules and their density being also ascertained, a value of W was successfully arrived at. The crucial test was thus within reach, namely of comparing this quantity with the constant w assigned by the kinetic theory to the gaseous molecular particle. It must be remembered that the latter quantity cannot be regarded as known with more than approximate exactness. The value of N based on the kinetic theory of gases may be taken as 60×10^{22} . The value of the corresponding number obtained by Perrin for his granules was 70.5×10^{22} .

Perrin's second series of experiments was in verification of Einstein's formula. The measurements required are of much

difficulty. Armed, however, with a method of producing granules of uniform size, and with satisfactory means, discovered in the course of the preceding research, of measuring the size, he was able to establish the formula very satisfactorily over a large range in size of granule, for granules of different material, and over a large range of variation of viscosity of the suspending liquids. The value 71.5×10^{22} so obtained for N shows practically perfect agreement with the value obtained by the first, radically different, method.

It appears, then, that Perrin's two lines of experiment lead to values for N (or for the mean kinetic energy of translation of the particle) which are of the same order as those assignable to a perfect gas. A more complete confirmation of the kinetic theory of the Brownian movement could hardly be looked for.

These experiments place the theorems of the kinetic theory on something like an experimental basis. Particularly of value are they in supporting the hypotheses of Van't Hoff and of Arrhenius in regard to solutions, when one remembers the strenuous opposition with which these views are still met by some chemists and physicists.

The accurate determination of the electronic charge e is perhaps of more interest even than that of N , and Perrin's value for the latter may be employed to furnish an independent estimate of the magnitude of the natural unit of electricity. Taking then $N = 70.5 \times 10^{22}$ we have

The Electronic Charge.

$$e = \frac{9654 \times 3 \times 10^{10}}{70.5 \times 10^{22}} = 4.11 \times 10^{-10} \text{ E.S.}$$

Perrin has also studied the Brownian movement of *rotation*, for which Einstein had again found an expression on the assumption that the kinetic energy of rotation is equal to that of translation. His measurements point to this equality, though probably the movements of rotation are not capable of sufficiently accurate measurement to justify the conclusion that absolute equality holds. This part of his work is of interest in connection with the theorem of the equi-partition of energy among the various degrees of freedom of a gas molecule, which has been advanced by Boltzmann, though not to the satisfaction of the majority of physicists.

Rotatory Movements.

V. Henri has examined the Brownian movement cinematographically, taking photographs every twentieth of a second, with a period of exposure of one-three-hundred-and-twentieth part of a second. By the employment of solutions containing a sufficiently small number of particles per unit volume it is thus possible to obtain numerous points on the path of the same particle. The trajectory so derived is of the kind one imagines on the kinetic theory, though, of course, the straight elements joining two successive points do not represent the path between two collisions, but give merely the displacement of a particle after an immense number of collisions with molecules of the solvent.

4. *Perrin's Work*.—The work of Perrin will now be considered in more detail. Let us consider first the different stages in the examination of the law of distribution.

**Preparation
of Uniform
Emulsion.**

(i.) *Preparation of a Uniform Emulsion*.—After trial of several colloidal solutions, M. Perrin found a satisfactory material in *gamboge*, a substance well known as a water colour. One method of producing an emulsion is to treat the gamboge with methyl alcohol, which dissolves a considerable fraction. On adding to the clear solution a considerable quantity of water, a yellow opaque emulsion is produced which consists, as shown by examination under the microscope, of a swarm of yellow granules of various sizes, all perfectly spherical. These can be separated by centrifuging from the containing liquid, which can then be replaced by pure water. A systematic procedure is next adopted comparable to the fractionation of a liquid mixture by distillation, whereby to produce an emulsion consisting of granules of any desired uniform diameter. The vessel of the centrifuge is filled to a definite height, say 10 cm., with the emulsion in water; the machine is turned at a definite speed, say 30 turns per second (corresponding to a centrifugal force 500 times greater than gravity). After a definite time, say 60 minutes, the motive power is cut off and the vessel allowed to slow down gradually. A jelly-like mass now occupies the bottom of the vessel, consisting of the aggregation of granules which have reached the bottom in the centrifuging process. Let a_1 denote the least radius which a granule, initially at the surface, must have to reach the bottom at the

moment centrifuging is stopped. All granules larger will, therefore, be found at the bottom of the vessel. But there will be present at the bottom some particles smaller than a_1 , which have had time to arrive there owing to their having been originally present in the lower layers of the emulsion. The supernatant liquid will consist of particles smaller than a_1 . By means of a syphon these particles may be removed. The vessel is now filled with distilled water to the original height, the sediment being well stirred to form once more a uniform emulsion. The centrifuging process is repeated in exactly the same way, and so on again and again, until finally the supernatant liquid is perfectly clear. All particles of radius less than a_1 will thus have been removed. Operations are now recommenced on this sediment, but with a slightly shorter time of centrifuging. The suspending liquid will then contain no particles of radius greater than a certain value a_2 , whilst none can be present of radius less than a_1 . By choosing the interval of centrifuging so that a_1 is very nearly equal to a_2 a practically uniform emulsion is finally obtained.

(ii.) *Distribution of Granules.*—Having secured a uniform emulsion, Perrin proceeded to examine the variation of concentration in successive horizontal layers when equilibrium had been attained. A shallow cylindrical vessel of height about one-tenth of a millimetre is taken (such as are made by Zeiss for enumeration of blood corpuscles), and in it a drop of the emulsion is placed, the top being closed in by a cover glass, which is then varnished round its edges to prevent evaporation. The preparation, carefully levelled, is then examined under a vertical microscope of very high power, in which case the depth of focus is small. Only those granules can be seen clearly which are contained in a very thin horizontal layer of thickness about 1μ ($\mu = \frac{1}{1000}$ mm.) To count the number of granules in any layer two methods have been employed. The first is that of instantaneous photography; this is, however, only applicable when the granules are relatively large. The second method is to place in the focal plane of the eyepiece an opaque screen of foil, in which a small circular hole is pierced. The field of vision is thus restricted, and the eye is able to take in at a glance the number of granules present at a definite instant (a maximum of five or six is best). A very large number of obser-

**The Law
of Distri-
bution.**

vations are made at a given level at equi-distant intervals of time, and the mean of these is taken. The level is then altered by a known amount, and the counting process repeated. Some thousands of readings are requisite to secure a reasonably high degree of accuracy. The concentrations of the granules in five equi-distant planes 25μ apart were obtained; the first plane being 5μ above the bottom of the vessel, to eliminate the possible influence of the boundary. To take one example: in the case of granules of radius 0.14μ , the numbers found were in the proportion 200, 170, 146, 116, 100, whereas the numbers required for geometrical progression are 201, 169, 142, 119, 100. The exponential law was thus proved to hold for gamboge particles of radius 0.14μ and upwards, and also in the case of an emulsion of mastic with particle radius 0.52μ .

Size of Granules.

(iii.) *Size of Granules.*—At first the law of Stokes was invoked for the determination of size of particle. The emulsion was placed in a capillary tube sealed at both ends and installed vertically in a thermostat. With a fine tube convection currents are avoided, and the granules fall steadily like a cloud, with a fairly sharp upper surface; their rate of fall being measured by a horizontal microscope. Equating Stokes' expression $6\pi a\zeta v$ to the apparent weight of a granule $\frac{4}{3}\pi a^3(\Delta - d)g$, a is determined.

A second method consisted in counting all the granules present in a small volume of the emulsion. If the total mass of the granules present is known, and the density of each granule, then the volume, and thus the radius, of a granule may be calculated. The counting is done in the flat cell already described, the bottom of which is divided into squares of 50μ side. The method depends for success on an observation made by Perrin that in a feebly acid medium the granules collect on the walls of the glass bounding the preparation. As soon as a granule touches the wall it sticks there. After a few hours, therefore, all the granules will have left the preparation and be found fixed to the walls. A camera lucida is then fitted to the microscope, and a copy made on paper of the squares and contained granules, first on the ceiling, then on the floor of the cell; whence the number present is obtained. The determination of the density is referred to later. The total mass of gamboge (or mastic) in a given volume of emulsion is determined by

evaporation of a known volume to dryness a little above 100°C . A glass-like mass is left whose weight remains constant, not altering even when the temperature is raised to 130°C . or 140°C . The determination of this weight furnishes the required datum.

A third method depends on the fact that the granules under the influence of acid often arrange themselves in rods composed of several granules. These rods are of sufficient length to measure accurately; and the component granules being distinguishable, and therefore capable of being counted, the diameter may be estimated.

The three methods give concordant results, providing incidentally a valuable confirmation of the applicability of the law of Stokes to such small granules. The most careful measurements were made on a gamboge emulsion. By the second method, after experiments in the course of which some 11,000 granules were enumerated, the value 0.212μ was obtained for the radius; whilst by Stokes' law the value 0.213μ resulted.

(iv.) *Density of Granules.*—The mass of resin in a given sample of emulsion may be readily determined by evaporating to dryness. The density of the residue is accurately found, and taken to represent the density of the granules.

5. The exponential distribution being established, and all the requisite data obtained, the equation of distribution allows of the determination of N , and that with a high degree of accuracy. Perrin's mean result, based on several series of experiments involving the measurement of some tens of thousands of granules, is that Avogadro's constant $N = 70.5 \times 10^{22}$.

**N from
Distribution.**

6. Perrin's next step was to seek for *experimental confirmation of Einstein's formula*, according to which the mean displacement of a particle in a given time depends only on the size of the particle and not on its chemical nature. Tiny metal globules and air bubbles should show the same degree of agitation if their sizes agree. The formula assumes the applicability of Stokes' law. Treating this assumption as justified by the measurements already described, a verification of the formula must be regarded as a vindication of the second proposition contained in that equation—namely, that of the equipartition of energy among the particles.

**Confirmation
of Einstein's
Formula.**

Two quantities require to be measured, namely the radius of the particles, and the mean square of the displacement in any definite direction in a given time. The former was determined as in the preceding investigation. For the measurement of displacement, the direction chosen by Perrin was a horizontal one; steady movement under the influence of gravity was thereby eliminated. The position of a selected granule was dotted in the camera lucida, the microscope being set vertical; five readings were generally made on each granule at equidistant intervals of half a minute.

**N from
Displacement.**

The measurements, made under various conditions, resulted in a satisfactory verification of the formula of Einstein. Thus on increasing the viscosity of the suspending liquid to five times by the addition of sugar, the displacement was reduced to the degree predicted. The law of variation with size was found to hold over a range of diameters from 0.4μ to 12μ . Taking the mean square obtained from over 3,000 displacements, the value 71.5×10^{22} was obtained for N.

We see then that the two experimental estimates of N, the number of particles per gramme-molecule, estimates arrived at by radically independent methods, agree so closely as to be practically identical. We have indeed in Perrin's investigations on the Brownian movement a remarkable confirmation of a brilliant suggestion. His daring work may well be regarded as a triumph of experimental skill, and its outcome is an important contribution to our knowledge of some fundamental natural constants.

**Rotatory
Movements.**

7. *Brownian Movements of Rotation.*—In the case of large spherical granules it is possible, owing to the presence of minute foreign inclusions, to observe persistent irregular movements of rotation, and even to measure their amount. Einstein has given a formula in this case too, and Perrin's measurements go far towards verifying the underlying assumption of the equality of the mean energies of rotation and of translation. Taking, for example, the case of spheres of mastic of diameter 13μ in suspension in a solution of urea, the root-mean-square rotation per minute obtained from 200 angular measurements was 14.5 deg., whilst the value calculated from the formula is 14 deg.

8. BROGLIE and EHRENHAFT have made experiments on dust particles electrically charged, obtaining data leading to an estimate of the charge carried. Here, owing to the small viscosity of the air in which the particles are suspended, the Brownian movement is much more violent than in a liquid.

**Dust
Particles.
Determina-
tion of e .**

Broglie, using the ultramicroscope, registered photographically the displacement of particles of tobacco smoke in an interval of three to four seconds. The value of N being assumed, Einstein's formula was applied, and thus the radius of the particles was calculated to be 4.9×10^{-6} cm. The particles were next charged by the passage of X-rays or radium radiation through the glass walls of the containing vessel. Their behaviour in the electric field applied between two parallel metal walls bounding the chamber showed that some of the particles were charged positively, others negatively, whilst the rest were neutral. The speed in unit field (electrostatic measure) was observed to be 27.5×10^{-3} cm./sec. By Stokes' formula the charge e could be equated to $6\pi a\zeta v$. The first set of observations supplied the value of a , the last set the value of v ; whence the value $e = 4.5 \times 10^{-10}$ E.S. was derived. In some experiments charges were obtained which were multiples of the above charge. The minimum value may be regarded as the charge of the electron.

Ehrenhaft, working with metallic particles, obtained the value $e = 4.6 \times 10^{-10}$ E.S.

CHAPTER VIII.

THE PRESSURE OF RADIATION.

1. When, early in the seventeenth century, Kepler pointed to the pressure of sunlight as the possible cause of the deflection of cometary tails away from the sun, he offered a suggestion that was quite reasonable on the corpuscular theory of light, which was then in vogue. Many efforts were made to put the corpuscular theory on a better footing by establishing experimentally the existence of a force of repulsion by light. De Mairan, the famous observer of the phenomena of auroras, for example, tried such experiments in or about 1754, but without success. Later, the failure of such efforts did duty as an argument against an "emission" theory. **Historical.**

In 1873 Maxwell pointed out, as a deduction from his electromagnetic theory, that light waves should exert a pressure upon objects on which they fall, in amount equal to the energy density, or radiant energy in unit volume immediately in front of the point of incidence. A few years later Bartoli deduced from entirely new considerations the existence of such a pressure, and started an idea which has proved very fruitful in the province of thermodynamic theory. Many years however, were permitted to elapse before experimental proof of the reality of such forces was secured. Crookes' researches on the radiometer, between the years 1873 and 1877, had revealed the play of considerable forces on the movable vanes; but, as Tait and others showed, these are only indirectly caused by the incident light, being the result of molecular bombardment by the surrounding gas on unequally heated surfaces. This molecular action may be, under certain conditions, thousands of times in excess of the pressure of the impinging light as calculated from the energy density. The radiometer effect and the influence of convection currents together constitute a gas action which in the earlier experiments effectually barred the way to any demonstration of a light pressure. In 1900

Prof. Lebedew, of Moscow, announced that he had succeeded in isolating and measuring this force. Nichols and Hull, in America, quickly followed, securing a remarkable degree of observation with theory. Prof. Poynting, in this country, has conducted a series of beautiful experiments on the tangential forces due to oblique radiation.

The existence of a radiation pressure has thus been firmly established. It would now appear that this result may be generalised: that in wave motion of every description there is a pressure normal to the wave-front equal in value to the energy density. In the case of sound waves, Altberg, working in Lebedew's laboratory, has quantitatively verified this; and Prof. R. W. Wood has constructed a "wind-mill" driven by sound waves.

To return to ether waves. The phenomenon under consideration has opened up several avenues of progress. It is the foundation of a new and important branch of thermodynamic theory—the *thermodynamics of radiation*—with which are associated the names of Bartoli, Boltzmann, Wien and others. It forms the basis of some very interesting astronomical applications, mainly at the hands of Arrhenius and Poynting. It leads to some considerations on the interaction of matter and ether which are of interest at the present moment when the foundations of the Newtonian mechanics are in question and the "principle of relativity" is bidding for the scientific ear.

INTERPRETATION OF RADIATION PRESSURE.

2. The existence of a pressure is an obvious consequence of an emission (or corpuscular) method of propagation of energy. It is of interest to see how the pressure arises in wave propagation.

(i.) *Light, heat and electrical waves* are, on Maxwell's electromagnetic theory, all of the same type. In the plane of the wave-front are tubes of electric and of magnetic force. Such tubes behave as though in a state of longitudinal tension, whilst they exert a lateral repulsion on adjacent tubes of the same sign. These lateral pressures are represented, in terms of the magnetic force \mathbf{H} and the electric force \mathbf{F} , by the well-known expressions $\mu\mathbf{H}^2/8\pi$ and $\mathbf{KF}^2/8\pi$. They combine to

form a resultant pressure which is equal to the energy density in the medium. Maxwell ("Electricity and Magnetism," Vol. II.) deduces his radiation pressure from these considerations, and proceeds to a calculation of the pressure on a square foot of the earth's surface due to strong sunlight, the pressure assigned being the energy in 1 cubic foot.

Sir J. J. Thomson regards the force, when the light is incident on a reflecting surface, in terms of the induced electric currents in the surface. A perfect reflector is a perfect conductor. The alternations of magnetic force cause induced currents confined to the surface layer of the conductor. These currents are in direction perpendicular to the tubes of magnetic force in the incident wave-front. The usual laws of mechanical force on a conductor carrying a current in a magnetic field will apply, and the conducting surface will be repelled.

(ii.) *Sound Waves*.—If we consider a mass of air contained in a cylinder in which fits a piston, it is easy to see that the confined air behaves very differently from an ordinary spiral spring. Even if the changes are at constant temperature, the application of Boyle's law shows that the increase of pressure for a given displacement of the piston inwards is appreciably greater than the decrease due to the same movement outwards. Still more must this be the case when the action is adiabatic; when motion inwards causes a rise, motion outwards a fall, of temperature. Thus, in a sound wave in a gas, since the gas pressure rises a little more above the normal in the compression half-period than it falls below in the rarefaction half, there is clearly an average pressure forwards on any surface on which the sound falls. Lord Rayleigh has shown, in the case of isothermal change, the equality of the forward pressure to the energy density in the wave.

**Sound
Waves.**

(iii.) *Transverse Waves in an Elastic Solid*.—Prof. Poynting has indicated a method of interpreting the forward pressure in the case where, for example, energy is being propagated along rotating steel shafting. During shear there is a force of compression along one axis of the shear and an equal force of tension along the second axis, which is perpendicular to the first. But these axes do not make equal angles on either side of the perpendicular to the planes of shear—i.e., with the direction of propagation of the shear. If e denotes the angle of

**Waves of
Shear.**

shear, one shear axis, that of compression, is turned by the amount $e/2$ nearer the normal; the other, along which there is tension, is turned by the same amount away from the normal. The effect is evidently to destroy the exact balance of these forces, yielding a slight excess of forward push over backward pull; and this difference works out to be equal to the energy-density in the shafting. In the diagram (Fig. 34) ABCD represents a section parallel to the direction of propagation. Particles at A and B are displaced to A' and B' in the plane of shear, whilst the disturbance is passing over the length AD. The compression axis DB' makes with DA the angle $\left(45^\circ - \frac{e}{2}\right)$, while the axis of tension CA' makes the angle $\left(45^\circ + \frac{e}{2}\right)$ with CB.

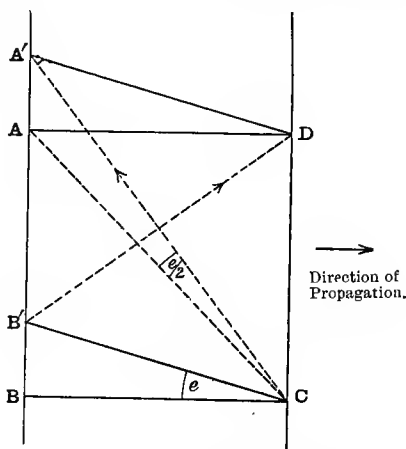


FIG. 34.—PRESSURE ARISING IN SHEAR WAVES.

There is a resultant pressure in the plane through CD in the direction of propagation.

The Energy Standpoint.

(iv.) *Interpretation from the Energy Point of View.*—Larmor has applied the principle of the conservation of energy to the problem, thereby deriving very simply the magnitude of the radiation pressure. This proof, as Poynting has observed, holds for any type of radiation in which the energy density for a given amplitude is proportional to the square of the

frequency. This relation, it will be noted, holds in the case of a single particle of matter moving with simple harmonic motion.

The simplest case to examine is that of a plane-radiating surface emitting plane waves. The surface will experience a pressure of recoil of value equal to the energy density. This may be seen by supposing the surface to move with velocity denoted by v in the direction of propagation of the radiation. Let V denote the wave velocity. The effect of the motion of the source is, in accordance with Doppler's principle, to raise the frequency of the emitted vibrations in the proportion $V/(V-v)$. If, then, E denote the energy density when the source is at rest, the measure of this quantity when the source is moving will be $E \cdot V^2/(V-v)^2$. In one second the source will have moved forward a distance v , and the energy emitted per second per unit area will, therefore, be crowded into the volume $(V-v)$ of the medium, the amount present being

$$E \cdot \frac{V^2}{(V-v)^2} (V-v) = E \cdot \frac{V^2}{(V-v)}.$$

When the source is at rest the energy emitted per second is EV . The source thus emits more energy per second when moving than when it is at rest. This implies a back pressure, p , against the source, and we may write

$$pv = E \cdot \frac{V^2}{V-v} - EV = E \cdot \frac{Vv}{V-v};$$

which, when $v=0$, becomes $p=E$.

EXPERIMENTAL WORK.

3. Great as the influence of the existence of a light pressure is in extending theory, the order of magnitude of these forces is not such as to make them of sensible importance in terrestrial mechanics. The steps taken by the physicists already named in disentangling these forces from insistent disturbing effects, and submitting them to accurate measurement, are of a high order of interest.

In the case of radiation falling normally on a surface which absorbs it completely, the pressure is equal to the energy per unit volume of the incident radiation. When the surface is

totally reflecting, the energy density is doubled by the superposition of the reflected beam upon the incident one, and the pressure is correspondingly doubled. In the former case the pressure caused by full sunlight at the earth's surface amounts to 0.59 milligrams per square metre (or 9.58×10^{-5} C.G.S.) ; for a total reflector it therefore exceeds 1 milligram per square metre. Such is the order of the forces in question. By means of the arc an intensity of perhaps 20 or 40 times that of sunlight can be applied.

The methods adopted in the three series of measurements referred to agree in that the light forces were made to act upon delicate vanes set at the end of a horizontal arm, producing a

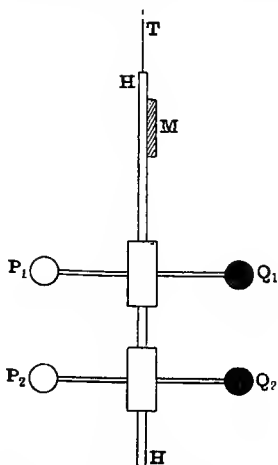


FIG. 35.—SUSPENDED SYSTEM (Lebedew).

couple which was opposed by the torsional control of a fine suspending fibre.

Lebedew.

4. The arrangements adopted by LEBEDEW are represented in Figs. 35, 36 and 37.

Two pairs of circular discs of platinum 5 mm. in diameter were mounted, as shown in Fig. 35 (elevation), at the ends of two light rods, these rods being attached perpendicularly to the vertical glass rod HH. The system was suspended by a glass fibre, T, in a glass globe about 20 cm. in diameter. The

discs P_1 , Q_1 have a thickness of 0.1 mm., and the lower pair, P_2 , Q_2 , a thickness of 0.02 mm. P_1 and P_2 are polished on both sides, whilst Q_1 and Q_2 are electrolytically coated with platinum black, the depositing currents being maintained for times in proportion to the thickness of the plates. M is a mirror used in conjunction with a telescope and scale. The method of illumination of the discs is shown in Fig. 36. Radiation from an electric arc at S falls on a lens, and by the mirrors and a second lens may be made to converge on either side of the disc A at will, the mirror M being for this purpose capable

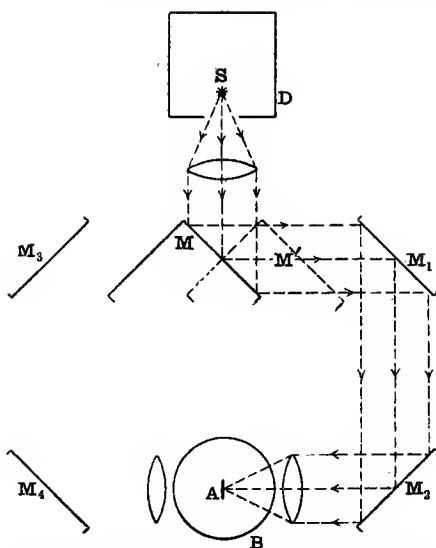


FIG. 36.—METHOD OF ILLUMINATION (Lebedew).

of movement to a second position M' , indicated by the dotted outline.

In addition to the light pressure on the disc there are the two forces constituting the gas action—namely, the radiometer effect and that arising from convection currents. By the use of very thin discs of metal the radiometer action was very much reduced, since it depends on a difference of temperature between the two faces of the disc. It is always in the same direction as the light pressure; but by comparing the

deflections obtained successively with the thick and thin discs it may be eliminated in the final calculations.

The effect of convection was very small, since the globe was exhausted of air to the utmost extent possible with a Sprengel mercury pump. The direction of the disturbing couple due to convection is, moreover, independent of the side of the disc on to which the beam is directed, the difference of temperature of the two faces being in this respect negligible. The mean of deflections taken with the light first on one face, then on the other, is thus free from the convection effect.

It is to be observed that the light pressure effect should, according to theory, be practically twice as great for the polished as for the black disc ; whilst the rise of temperature

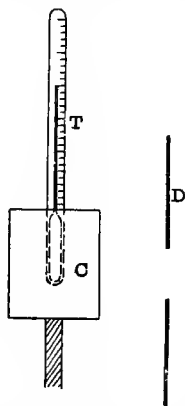


FIG. 37.—CALORIMETER (Lebedew).

in the case of the black disc will be greater than for the polished one, and consequently the gas action greater. A comparison of the deflections in the two cases showed that the correction for gas action was satisfactorily small.

The deflections obtained were reduced to the equivalent couples in the usual way, by observation of the times of vibration of the suspended system before and after the addition of a known moment of inertia.

The absolute measure of the intensity of radiation employed was obtained by a simple calorimetric apparatus (*see* Fig. 37). A plate D, containing an aperture of area equal to that of the

discs, was placed in the globe so that the aperture coincided precisely with the position previously occupied by a disc. Behind it was a small copper cube weighing 30 grammes, with one face C blackened. In a hole drilled in the cube was embedded the bulb of a thermometer, T, with a little mercury to ensure conducting contact. The rise of temperature in a given time was obtained when the light was directed on to the cube under the conditions of the main experiments. A simple calculation supplied the required datum. Lebedew was finally able to announce the discovery of a pressure equal, within the limits of error of experiment, to that predicted by Maxwell.

5. NICHOLS and HULL's researches involved an exhaustive examination of the nature of gas action. Experiments were made at various pressures of the air surrounding the suspended system. Whilst radiometer action becomes more pronounced as exhaustion proceeds, the effect of convection currents is on the other hand reduced. It is thus possible to pit these disturbing effects against one another. In the apparatus employed by Nichols and Hull a zero resultant effect was found to be most nearly secured when the pressure was about 16 mm. of mercury. **Nichols and Hull.**

The vanes on which the radiation was received were circular discs of thin glass silvered on one side, the silver film being polished on its outer side.

The gas action is independent of the face of the disc on which the radiation first falls. The incident rays have already been sifted by the glass walls of the containing vessel, so that in the case where the radiation falls on the unsilvered face of the disc it is transmitted entirely by the glass, and falling on the silver film raises its temperature to the same extent as when the beam is directed first on the silvered face. Thus, when the incident beam meets the silvered face first, the light pressure and the slight outstanding radiometer action are in the same direction; when the beam falls first on the unsilvered face the light pressure and the radiometer action are opposed. The convection effect is likewise independent of the direction of incidence. Gas action is therefore corrected for by taking the mean of the deflections within the light incident first on the one, then on the other face of the discs.

The observations were "semi-ballistic"; the radiation was

allowed to fall upon the vanes for a time (some six seconds) equal to one quarter the period of oscillation of the suspended system, and the throw was observed. The object of this procedure was again to reduce the gas action, which takes a few minutes to develop fully.

The authors appear to have secured agreement to within one per cent. between the light pressure measured and that deduced from the energy measurements.

A very simple method was subsequently proposed, and carried out by Hull, with the object of eliminating the gas action. It consists in enclosing the vanes within airtight thin-walled glass cells, vane and cell being in rigid connection (see Fig. 38). The thin glass walls of the enclosure are practically at the same temperature as the surrounding gas, since, as already explained, they do not absorb any of the incident radiation. Forces on the vanes are attended by equal reactions on the walls of the containing cells, so that the couple on the suspended system is nil. This device proved highly successful.

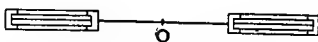


FIG. 38.—HULL'S SUSPENSION.

The light repulsion was measurable at practically any pressure from that of the atmosphere downwards in the containing vessel. Gas action was reduced to two per cent. of the light pressure. With this arrangement the pressure due to light may be comparatively easily demonstrated.

Poynting

6. PROF. POYNTING has initiated a series of experiments suggested by a fresh point of view of the radiation pressure, that, namely, in which the radiation is regarded as a stream of momentum. Not only is energy carried by the undulating medium, but also momentum, the amount of the latter in unit volume being obtained by dividing the energy density by the velocity of propagation. When light is incident on matter, whatever momentum the light loses the matter gains, and *vice versa*. A simple analysis on the basis of the principle of the Conservation of Momentum shows that at total reflection, and at refraction, the light forces are normal to the surface for all angles of incidence. At reflection the surface is urged in

the direction of the incident light ; at refraction the force is in the opposite direction—a pull instead of a push—in the case where the passage of the light is into the denser medium. When absorption takes place the tangential component of the light stream, as well as the normal component, is destroyed ; wherefore the surface experiences a tangential force in addition to the normal one.

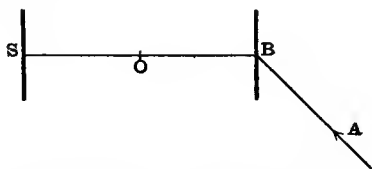


FIG. 39.—DEMONSTRATION OF TANGENTIAL FORCE (Poynting).

These consequences have been verified by Prof. Poynting and Dr. Barlow. Two experiments due to them will be adduced. In the first, two discs of glass, one silvered (S) and the other blackened (B), were fixed vertically at the ends of a thin horizontal glass rod, the system being hung by a quartz fibre attached at O, as shown in the diagram of Fig. 39. A beam A from a Nernst lamp was allowed to fall at an angle of 45 deg., first on one disc then on the other. The arrangement is such that normal forces acting uniformly over the discs pro-

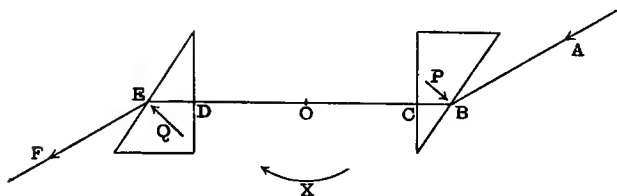


FIG. 40.—DEMONSTRATION OF FORCES AT REFRACTING SURFACES (Poynting).

duce no couple on the system. Radiometric action is thus eliminated—a noteworthy advantage of this disposition of the discs. Any torque observed is, therefore, a measure of the tangential forces acting.

The deflection when the stream was directed on B was very much greater than when directed on S. In a particular experi-

ment the torque observed in the former case was 21×10^{-6} cm. dyne, whilst the value calculated from the energy was 22×10^{-6} cm. dyne.

A second experiment, showing the effects at refraction, is indicated in the diagram (in plan) of Fig. 40. Two glass prisms, with refracting angle 34 deg., were mounted at opposite ends of a glass arm 3 cm. long, the system being then hung from a quartz fibre attached at O. A beam of light, ABCDEF, entered one prism at B, emerging at E from the second prism. The system turned in the direction shown by the arrow X. The forces acting have their points of application at B and E, being normal to the surfaces, and of sign represented by the arrows P and Q. The order of magnitude of the deflections observed was as expected.

7. Further additions to the list of beautiful experiments on the forces due to light might be made. Simple mention must suffice of a wonderful demonstration by Prof. Lebedew of the pressure on an absorbing gas, a consummation which could hardly have been thought possible in view of the small absorbing power and the tenuity of gases.

In the next chapter will be put forward an account of the three lines of inquiry which take their origin in the fact of the radiation pressure.

CHAPTER IX.

THE PRESSURE OF RADIATION (*Continued*).

1. Though every transmission of energy by wave motion is accompanied by a pressure on absorbing or reflecting bodies in its path, the interest of the subject lies practically entirely in the domain of ether waves. It has been observed how the existence of this pressure has been arrived at theoretically from three different points of view. Maxwell deduced it as a consequence of the lateral repulsion which lines of electric force exert on one another; Bartoli rested it upon the Second Law of Thermodynamics; whilst Larmor finds a basis for it in the principle of the conservation of energy. The labours of Lebedew, Nichols and Hull, and Poynting have furthermore placed it upon a secure experimental basis. The fact, or principle, of Radiation Pressure comes therefore with strong credentials into the field of modern physics. No stronger, however, than is needful; for, like the aspiring young politician who directs his attack upon the lion of the opposing party, the principle has joined in a challenge of the fundamental axioms of dynamics, the Newtonian Laws of Motion. Its work on constructive lines has been the creation of the Thermodynamics of Radiation. In regard to certain problems of cosmic physics, such as the phenomena of comets and meteorites and the solar corona, this force promises, if not completely to solve old questions, at least to contribute decisively towards their complete explanation.

THE THERMODYNAMICS OF RADIATION.

2. This branch of the subject of Heat depends upon the idea of radiant energy as the "working substance" of a heat engine. Enclosed in the model cylinder with tightly fitting frictionless piston, radiant energy exerts a pressure on the enclosing walls. A diminution of volume implies work done *on* the radiant

energy, and vice versâ. Proceeding by the method of the Carnot cycle, laws have been derived bearing on the connection between radiation and temperature, and on the distribution of energy in the spectrum of a hot body.

**Bartoli's
Argument.**

It will be interesting to recall the reasoning by which at the outset Bartoli showed the necessity for postulating a radiation pressure. He imagines a cylinder whose sides are totally reflecting, whilst the ends are closed by discs of fully absorbing material, kept at constant, though different, temperatures (*see* Fig. 41). Near the end A (at the higher temperature) is a totally reflecting, tightly fitting slide, q , which can be pushed in so as to cut off A from the cylinder below, or drawn out so as to

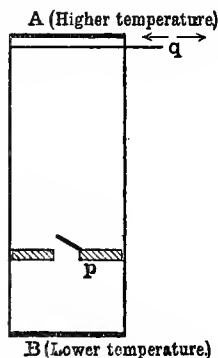


FIG. 41.—BARTOLI'S IDEAL ENGINE.

establish free communication. A piston of totally reflecting material, p , in which is a valve, is also provided. We have thus at command a mechanism for pumping heat energy from B to A. For suppose q closed, and p in its lowest position, close to B, the valve being open. The space between p and q is filled with black-body radiation of quantity and quality corresponding to the temperature of B. Close the valve, open q , and move the piston up to q . The radiant energy is thus swept into and absorbed by A: q may now be pushed in, the valve in p opened, and p moved down to B, completing the cycle. Clearly an unlimited quantity of heat may thus be transferred from the cold body to the hot one. This, by the second law of thermo-

dynamics, implies the expenditure of work; and this is only possible if the radiation that is swept forward presses back on the advancing piston.

3. To perform the isothermal and adiabatic transformations of the Carnot cycle two kinds of enclosing wall are needed to our working chamber. For the isothermal operation the walls must be of conducting and absorbing material; for the adiabatic operation they must be capable of totally reflecting radiation of all wave-lengths. In the first case the enclosed radiation will be in equilibrium with the walls of the enclosure, depending in quality and in quantity only upon the temperature of those walls. This principle, which is due to Balfour Stewart and Kirchhoff, is of fundamental importance. It implies that the radiation falling upon (or proceeding from) any part of the walls is precisely the same in every respect as that which would be emitted at the same temperature by the same area of surface of a material possessing the power of completely absorbing ether radiations of every type, transmitting none and reflecting none. Such a body has been termed a "black body." At any given temperature such a body will emit radiations of all wave-lengths from zero to infinity. The amount of energy radiated between the wave-lengths λ and $\lambda + d\lambda$ may be written $e d\lambda$. The value of e will depend upon the value of λ , rising from zero for zero wave-length, up to a maximum, and falling again to zero at the other extremity of the scale. No material can possess, at any particular wave-length, a greater value of e than does our black body. As the temperature rises, e rises throughout the whole range of wave-length, until the amount of energy radiated within the limits of the visible spectrum is sufficient to cause the body to glow. The general term "black body" is therefore being discarded in favour of the more appropriate alternative "full radiator."

No material surface has been found having full radiating power. The colour of bodies as seen in sunlight is of course immediate evidence of the existence of selective radiating power, and even a thick coat of lampblack or of platinum black falls short by two or three per cent. (to an extent, however, depending on the wave-length) of the emissive power of the full radiator. The property of the isothermal enclosure permits, happily, of the practical attainment of this desideratum. If

**The Black
Body, or
Full Radiator.**

a small hole be made in the wall of the enclosure, the radiation escaping thereby will evidently be the full radiation corresponding to the temperature of the enclosure. This idea, suggested by Kirchhoff, was first put in practice by Wien and Lummer in 1895.

The Stefan-Boltzmann Law.

4. Boltzmann worked out in 1884 the consequence of submitting full radiation to a Carnot cycle. The result that emerged was the law of variation of the rate of total radiation of a full radiator in proportion to the fourth power of the absolute temperature. This law had already been assigned by Stefan from an examination of purely experimental numbers, and he supposed the law to apply to all bodies. It is now known from observation that this is not strictly the case, the divergence being greater the further removed the body is from the full radiator. For bright platinum the variation is more nearly as the fifth power of the temperature.

Wien's Laws.

5. Two other laws, due to Wien, relate to the distribution of energy in the spectrum of a full radiator. They were deduced by considering the behaviour of radiant energy during an adiabatic change of volume, that is, when the energy is enclosed by totally reflecting walls. As the volume is diminished the energy density rises, not only because the amount of energy present to begin with is compressed within a smaller space, but further because of the work spent in overcoming the radiation pressure, which work is transformed into the equivalent amount of radiant energy. If the radiation taken is full radiation, it remains full radiation throughout the change. Thus during contraction the temperature rises, its value altering inversely as the linear dimensions of the enclosure—that is, for a spherical enclosure, inversely as the radius.

The effect on each wave-length may be followed by operating with monochromatic radiation. As the sample taken is adiabatically compressed, the wave-length diminishes. Wien deduced this by the application of Doppler's principle—a principle which is very familiar in regard to sound vibrations, as well as in its application to the displacement of the lines of stellar spectra arising from motion in the line of sight. Clearly light incident on the approaching walls of the contracting,

totally reflecting enclosure will return with wave-length shortened, and the calculation shows that the change is in the same proportion as that of the linear dimensions of the enclosure : the energy density of the monochromatic radiation at the same time alters as the inverse fourth power of the linear dimensions. Collecting these results in equational form we have, if r =radius (for spherical enclosure), θ =absolute temperature, e =ordinate of spectral energy curve, E =total energy density :—For full radiation

$$E \propto \theta^4, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (a)$$

$$\theta \propto 1/r; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (b)$$

and for monochromatic radiation (the radiation between narrow limits λ and $\lambda + d\lambda$),

$$\lambda \propto r, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (c)$$

$$ed\lambda \propto 1/r^4. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (d)$$

The last two results may be applied to each element of full radiation. In a totally reflecting enclosure there will be no interchange of energy between the different wave-lengths, the changes for any particular element of radiant energy being independent of the presence of other elements in the same space. By conducting an adiabatic operation it is thus possible to observe the density of full radiation and the temperature vary together; and confining attention to one particular wave-length, to follow the way in which at the same time the wave-length alters. The law of the operation is summed up in the equation, obtained by combining (a), (b), (c) and (d),

$$e = c_1 \theta^5 f(\lambda \theta), \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (A)$$

$f(\lambda \theta)$ being a function of the product of λ and θ which the theory does not further define; whilst c_1 is an absolute constant. This equation tells us that if energy curves be drawn with e as ordinate, $\lambda \theta$ as abscissa, the curves have, for any given value of the abscissa, ordinates proportional to the fifth power of the absolute temperature. If the spectral energy curve—that is, the curve of distribution of energy with wave length—is known for full radiation at any one temperature, it is therefore known for all temperatures. Again, it is clear that the value of $\lambda \theta$ for which e is a maximum is the same whatever the temperature.

Denoting this wave-length by λ_m , and the corresponding value of e by e_m , we thus have

$$e_m = \text{constant} \times \theta^5, \quad \dots \dots \dots \text{(I.)}$$

$$\lambda_m \theta = \text{constant} \quad \dots \dots \dots \text{(II.)}$$

These practical consequences of (A) are Wien's Laws of Radiation. They apply, like the Stefan-Boltzmann law, to full radiation only.

Experimental Confirmation.

6. Turning to the experimental side, spectral energy curves have been obtained by Lummer and Pringsheim, and by Paschen

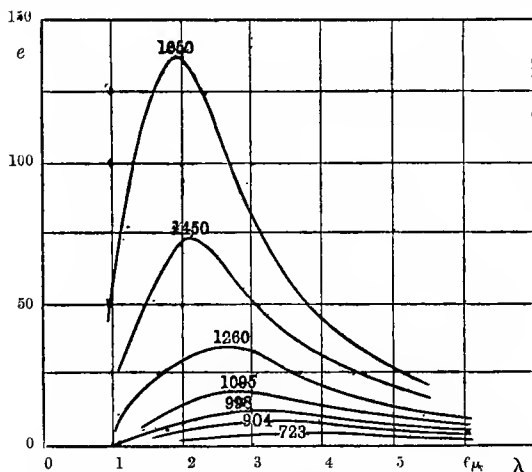


FIG. 42.—SPECTRAL ENERGY CURVES OF FULL RADIATION.
(Lummer and Pringsheim.)

and others, at various temperatures up to the limit of range of the gas thermometer; the source being a constant temperature enclosure with small opening, electrical heating being employed.

These curves are in extremely good agreement with Wien's two laws, and with the Stefan-Boltzmann law. Lummer and Pringsheim's curves are reproduced in Fig. 42. From this figure Fig. 43 has been constructed, showing that the maximum value of e occurs for the same value of $\lambda\theta$ at all values of θ .

From their numbers the values of the constants may be obtained, and we may write

$$\begin{array}{lll} e_m = 2188 \times 10^{-17} \theta^4 & \cdot & \cdot & \cdot & \text{(I.)} \\ \lambda_m \theta = 2930 & \cdot & \cdot & \cdot & \cdot & \text{(II.)} \end{array} \quad \text{(Wien's laws)}$$

also

$$E = \int e d\lambda = \frac{\sigma}{v} \theta^4 = 1.71 \times 10^{-15} \theta^4 \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \text{(III.)}$$

(the Stefan-Boltzmann law),

λ being expressed in microns ($\mu = 10^{-3}$ mm.), and e in ergs per cubic centimetre; whilst v denotes the velocity of light. The number taken for σ is Kurlbaum's value.

7. For the purposes of *high temperature measurement* we have here three methods at disposal, each leading to temperature on

**Measurement
of High Tem-
peratures.**

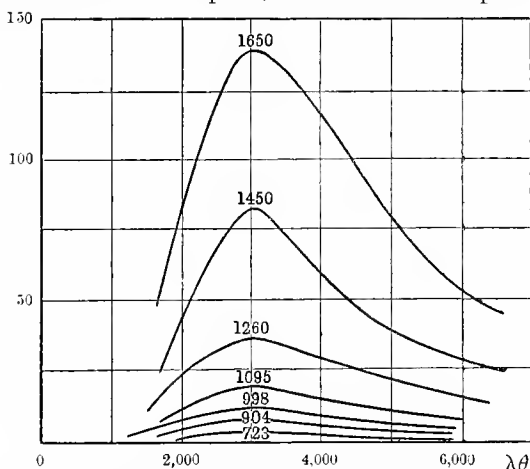


FIG. 43.— e AS A FUNCTION OF $\lambda\theta$.

the absolute thermodynamic scale. The gas thermometer does this important service with great accuracy up to $1,200^{\circ}\text{C}$. The formulæ of the resistance pyrometer or the thermo-electric couple are merely empirical, and their use beyond the limit named depends on the vicious method of extrapolation. If, however, we are able to measure e_m , or λ_m , or E , the laws of radiation permit of the determination of temperatures however elevated.

The proviso that these laws only hold for a full radiator causes, it must be said, a distinct limitation in their practical application. Heated surfaces do not behave as full radiators,

and our ideal constant temperature enclosure is not always available. Bodies do not even behave as "gray" bodies, with emissive powers in constant proportion, at all wave-lengths, to those of the full radiator. In other words, bodies radiate selectively. Even lampblack and platinum black are not excluded from this category.

A metal—for example, bright platinum—would be expected to show considerable selective properties. If r denote the reflective power, the emissive power will be $1-r$. Now r varies considerably with λ , being practically unity for the extreme infra-red waves, as far as, say, $\lambda=10\mu$, but falling off considerably as one passes to shorter wave-lengths. For the experimental data in the case of metals, interesting besides as showing the connection between reflecting power and electrical conductivity, we are largely indebted to the researches of Rubens and Hagen.

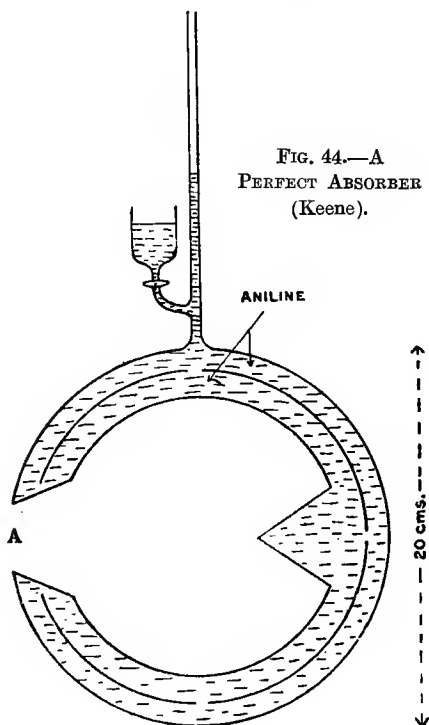
Owing to the above considerations the published determinations of the temperature of incandescent carbon and metal filaments, and of flames and incandescent gas-mantles, are to be accepted with much reserve.

The Perfect Receiver.

Again the legitimate application of the laws of radiation to temperature measurement requires that the *receiver* of the radiation should behave as a perfect absorber. It has been generally taken for granted that a thick coating of lampblack or platinum black satisfies this requirement. In some cases the bolometer employed has been placed at the centre of a polished sphere, thereby securing the return of the radiation initially reflected. The constant temperature enclosure with small aperture to admit the radiation satisfies the required condition practically perfectly. Féry, to whom we are indebted for perhaps the most satisfactory type of radiation pyrometer, employed a hollow cone forming part of a sensitive alcohol thermometer, the radiation being received on the blackened inner surface. Some of the results of his work are of much interest, though their accuracy has been challenged. He states that the best platinum black reflects 18 per cent. of the incident radiation from a full radiator at 100°C . He proposes in place of Kurlbaum's value 5.32×10^{-5} ergs per second per cm^2 for σ in the Stefan-Boltzmann formula the much higher value 6.30×10^{-5} ("Comptes Rendus," April, 1909). The determination of this constant has since been undertaken by several

other workers, from whose results it may be concluded that probably Kurlbaum's value is low, though not to the extent indicated by Féry's number.

The receiver used by Keene ("Proc. R. S." Jan., 1913) shows a distinct advance over that of Féry. It is represented in Fig. 44. It consists of an aniline thermometer, the bulb having double spherical walls of thin copper. The capacity is about 2 litres,



the bore of the stem being 1 mm. Radiation passes through an aperture A about 2 cm.^2 in area and falls on the interior lampblackened surface of the bulb. In order to reduce error due to direct reflection the portion of the surface opposite to the aperture is shaped in the form of a cone. To prevent direct radiation through the aniline from the inner surface an inter-

mediate shell of copper is also provided. The sensibility is such that 1 mm. rise of the meniscus corresponds to a rise of temperature of 0.0005°C. Water-cooled screens should be employed as usual to limit the radiation received strictly to the aperture at A.

Planck's Formula.

8. With regard to the *exact form of the spectral energy curves* it will be observed that, as expressed in equation (A), this remains indeterminate, since $f(\lambda\theta)$ is not elucidated. Several attempts have been made to solve this important outstanding problem. Wien has obtained $f(\lambda\theta) = e^{-c_2/\lambda\theta}$, whilst Planck has proposed the formula $f(\lambda\theta) = \frac{1}{e^{c_2/\lambda\theta} - 1}$, c_2 being a constant in

each case. These formulæ have proved of great value. Wien's formula agrees closely with experiment provided λ is not too large, whilst Planck's formula appears to hold very closely over the whole range studied.

Both formulæ depend however on special assumptions as to the nature of the radiating molecule, and cannot be regarded as possessing the same degree of authority as the laws previously cited.

Quality and Efficiency of Light Sources.

9. The laws of Wien throw light on the directions in which we must look for more efficient sources of illumination. The eye has adapted itself to the sun's light, whose quality is approximately that of the perfect black body. The maximum in the spectral energy curve—of course after passage through our atmosphere—is at 0.5μ , and this is the region of maximum sensibility of the human eye. The ideal artificial source should copy the spectral energy curve of sunlight. Wien's Second Law tells us that a black body source would do this if its temperature were about 6,000°C. The following table gives approximately some temperatures attained in practice:—

	Temperature.
Flame of Argand lamp	1,500°C.
Incandescent Welsbach mantle	1,650°C.
Incandescent carbon filament	1,800°C.
Bunsen flame	1,870°C.
Incandescent tungsten filament	2,100°C.
Acetylene flame (in air).....	2,300°C.
Oxy-hydrogen flame	2,400°C.
Oxy-acetylene flame	(over) 3,000°C.
Positive pole of carbon arc	3,600°C.

Most of the above are employed as sources of light, and in every instance we have to deal with *temperature radiation*: the ordinates in the spectral energy curve falling below those of a black body at the same temperature, whilst with increasing temperature the energy-maximum moves to the side of shorter wave-length. The radiant efficiency, that is, the ratio of the energy emitted within the limits of the visible spectrum to the total energy radiated, is a function of temperature. In the case of the ideal black body the efficiency so defined is less than 2 per cent. at $1,800^{\circ}\text{C}.$; at $6,000^{\circ}\text{C}.$ it is 49.7 per cent., whilst above that it diminishes as the energy-maximum is carried towards the violet end of the spectrum. From the point of view of efficiency thus defined, metals and certain other substances may possess an advantage over the black body. The merits of the tungsten filament lamp are due not only to the high temperature at which it can be run, but to the fact that in accordance with its metallic character the energy emitted at the long wave-lengths is very feeble. The same causes probably account for the efficiency of the Welsbach mantle. For the same amount of energy supplied, the temperature of the source in both these cases is above that of the black-body filament or mantle. Thus a thermocouple placed in a Bunsen flame is found to record a higher temperature if covered with the Welsbach mixture than if uncoated or blackened. The *selective radiator* has a great economic advantage as a source of light.

**Temperature
Radiation.**

From the table it appears that a superior "limelight" might be expected by the use of the oxy-acetylene flame playing upon a refractory surface, say, of magnesia (which can support a temperature as high as $3,000^{\circ}\text{C}.$ without melting).

The ordinary carbon arc, in which the light is due mainly to the incandescent positive carbon, owes its superiority to the great lead in temperature that it holds over any other terrestrial source of light. This temperature of $3,600^{\circ}\text{C}.$, independent of the strength of the electric current passed, appears to be the boiling point of carbon, which at ordinary pressure evaporates without melting.

In the phenomenon of *luminescence* we have the possibility of far greater efficiencies of transformation of energy into visible radiation. A stick of phosphorus in air, or Balmain's luminous paint after exposure to sunlight, are luminous at

**Lumines-
cence.**

ordinary temperature. The glowing gas in the vacuum tube through which the electric discharge is passing is at a comparatively low temperature; and in contrast to temperature radiation the spectrum consists of lines, which do not shift their position as the intensity of the exciting current is increased. Gases or vapours may conceivably exist for which the spectral lines lie wholly or mainly within the visible region. Up to the present the practical sources of light depending on electro-luminescence are the nitrogen tube (Moore), the mercury arc, the flame (calcium) arc, and the titanium arc. The efficiencies, in the sense of candle-power per watt, are very high in the cases of the two last named; being about 4 for the calcium-fed arc, whereas in the most efficient incandescent filament lamp, the tungsten lamp, it is only 1 candle per watt. In regard to *quality*, on the other hand, there is no reason to expect from luminescent sources any near approach to the spectral energy curve of sunlight. In the mercury arc, with its few green and blue lines, the failure is palpable. The flame arc, in which one electrode at least consists of carbon impregnated with calcium salts, is orange yellow in colour. In the so-called magnetite arc (with its negative electrode of magnetic oxide of iron to serve as the conductor, with which is mixed the oxide or carbide of titanium), the spectrum, that of titanium, consists of a very great number of lines close together, and the emitted light may fairly be described as white. This last-described arc is as yet comparatively unknown in this country, whilst the calcium flame arc is in wide use.

THE INTERACTION OF ETHER AND MATTER.

**Are Newton's
Laws of
Motion
Strictly True?**

10. This question has long attracted the attention of physicists, and has been the subject of some famous experiments; for instance, those of Fizeau, and Sir Oliver Lodge, and Michelson and Morley. The pressure of radiation is a positive example of such interaction. Consider a conducting ball, one hemisphere of which is blackened, the other bright. Let it contain some source of thermal energy, such as an electric battery on closed circuit, which maintains the temperature of the surface of the ball at some definite value. The blackened half will radiate more energy than the polished half. The reaction on the former side will therefore be greater than on the

latter, and the sphere will move off with acceleration, polished side foremost. How do Newton's Laws I. and III. apply to this? We cannot say that a corresponding equal but opposite force will be manifested on some other material body in the region round. There is none necessarily present. The principle of the conservation of momentum will be satisfied if we assume the ether itself to stream away in the opposite direction. In doing this we are invoking the interaction of ether and matter, the ether being taken to possess inertia like ordinary matter.

Or take another example, posed by Poynting in his memoir "Radiation in the Solar System": namely, the case of two equal spheres at the same temperature, and subject only to the forces arising from their own radiation pressure and their mutual gravitational attraction. Since the repulsive effect of one sphere on the other depends on the product of their cross-sectional areas, whilst the gravitational pull is proportional to their masses—that is, to the sixth power of the radius—it is evident that for a sufficiently small size of sphere the radiation pressure, comparatively insignificant for very large spheres, may be made to balance the gravitational pull. This will occur for a diameter of 40 cm., assuming the density to be that of water, the temperature to be $27^{\circ}\text{C}.$, and the spheres to be full radiators. If now the temperature of one sphere A be raised, that of the other B lowered by a corresponding amount, then the balance of forces is destroyed. Both B and A will set off with the same acceleration, A chasing B!

Even though we have only one body with perfectly uniform surface and at one temperature throughout, the emission of radiation brings into play an unbalanced force, if the body is in motion with respect to the ether. The Doppler emission effect will come into action, causing a heaping up of energy in front, a thinning out behind; with a consequent excess of back pressure on the advancing side, this excess being proportional to the velocity of the body. The body will therefore slow down. In the cases of the accelerating bodies previously considered the acceleration will fall off and a certain limiting speed will be attained, just as for a falling raindrop.

Confining our observation, as we must in practice, to sensible material bodies—ignoring, that is, a massive ether—the breakdown in the Laws of Motion is unescapable; for, as we have

seen, the existence of the radiation pressure, whether in action or reaction, is an experimental fact.

Variability of Mass.

11. One may recall similar conclusions which have been arrived at from a different point of view, bearing on the possible variability of mass of a body. The moving electron increases in mass with increase of speed. For slow speeds this effect is inappreciable, being, at the rate of the earth's movement round the sun, about one part in 100 millions, whilst at a speed one-tenth the speed of light the increase is still under 1 per cent. The rate of increase beyond this point however becomes very large, tending to infinity as the speed of light is approached.

Again, the effective mass of an atom may depend not only on the number of electrons it contains, but on their configuration. As the energy of the atom diminishes, it has been supposed that the mass of associated ether diminishes too. If this attached ether is not subject to gravity, a difference in the ratio of mass to weight may be expected in the cases, say, of radium and its probable parent uranium, since the amount of energy lost by the latter in passing into the former is very considerable. Simple pendulums of the same length would then vibrate in periods depending on the nature of the material of the bob. Such is the line of reasoning taken by Sir J. J. Thomson, whose experiments however have not as yet shown any differences. If, on the other hand, the associated ether is subject to gravitation just like ordinary matter, loss of weight should take place as the result of intense chemical interaction in closed vessels, and this might be put in evidence by the chemical balance. So far as experiments in this direction have gone, the results are likewise inconclusive.

Now a change in mass involves the breakdown of Newton's Second Law of Motion. It appears then that whilst in the case of the single negative electron this change does occur, no evidence of it is yet available in the case of matter, the atoms of which, according to modern views, contain electrons in numbers of the order of their atomic weights.

ASTRONOMICAL APPLICATIONS.

Effect on Meteorites.

12. The pressure of sunlight constitutes a repulsive force which, as we have seen, is insignificant except in the case of

small bodies. This effect has been considered in application to the fine dust of which the tails of comets are probably composed ; also to the larger particles constituting meteorites.

Prof. Poynting's calculations as regards meteoritic stones are very suggestive. The repulsive action of sunlight may by its cumulative effect seriously modify the motion of such bodies. Imagine a swarm of meteorites, of various sizes, moving in a circular orbit about the sun. If at distance r , and moving with speed v , the gravitational acceleration on one of the particles of the swarm will be equal to v^2/r . But if we take the light push into account, the acceleration for the same value of r is less ; that is, v is less, and this amounts to an increase in the period of revolution. As this effect takes place to an extent increasing as the body becomes smaller, a sorting action results, the smaller particles lagging behind the larger, so that ultimately a ring will be formed. It is even possible that the rings of Saturn may have been thus evolved.

Again, if the orbit is an elliptical one, there will be a steady tendency towards a circular one, due to the Doppler effect. Motion nearer to the focus will be resisted, likewise motion away ; so that the body tends to move everywhere perpendicular to the line joining the body to the sun—in other words, to possess a circular orbit.

A third effect is due to the quasi-viscous resistance acting in the line of the body's motion, as already explained. Hence the body slowly falls a victim to the solar gravitational pull. Steadily it spirals inwards, quicker the smaller its size, the period of revolution becoming progressively less. Particles of 1 cm. diameter will reach the sun (from a distance equal to that of the earth) in 90 million years ; if a thousandth of that size, in a thousandth of the time. Encke's comet is well known for the steadily diminishing interval between its successive returns ; and Encke regarded this fact as evidence of the presence of a resisting medium increasing in density towards the sun. This celestial object may ultimately prove to be shortening its period in obedience to light forces.

13. The calculations have a new interest when the particles are very much smaller, such as compose, at all events partially, the "coma" of a comet. Lebedew was one of the first to suggest the pressure of sunlight as the cause of the well-known

**Effect on
Comets.**

deflection of the comet's tail away from the sun. His diagram is here reproduced (Fig. 45). *S* denotes the sun at the focus of the ellipse *OR* which represents the path of the nucleus under gravitational forces only. Both the gravitational pull and the light pressure due to the sun follow the law of the inverse square. The resultant acceleration thus follows the same law, its value falling off the smaller the diameter of the particle, and also the smaller their density. *OR*₁, *OR*₂, &c., represent the orbits of successively smaller particles originally together at *O*. The line *OL* represents the path of particles for which the two forces exactly balance.

The region to the right of *OL* is of considerable interest. Olbers' calculations of a century ago showed that cometary matter was repelled from the nucleus with a force much more

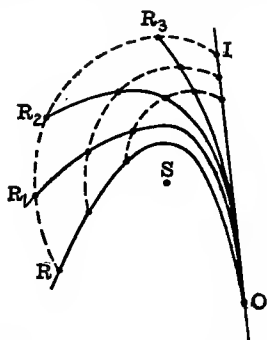


FIG. 45.—MOVEMENT OF COMETARY PARTICLES (Lebedew.)

powerful than the opposing attractive force of solar gravity. Bredichin has classified comets' tails on the basis of the ratio between the repulsive and the attractive force. In one class the solar attraction is only partially neutralised. At the other extremity of the scale he places some comets for which the repulsion exceeds the attraction 19 times. Still higher ratios have since been observed—for example, 40·5 in the case of Swift's comet. Arrhenius has shown that radiation is capable of furnishing ratios as high as this.

Far higher ratios, apparently beyond the power of radiation pressure to produce, have been calculated by Eddington as occurring in the envelope existing on the sunny side of the

nucleus. These numbers, however, depend upon the use of the "fountain" theory of formation of the envelope, and this theory is perhaps hardly yet out of the region of mere surmise.

Arrhenius' calculations showed that in order for repulsion to exceed attraction the particles must be very small, with diameters of the order of 1μ and under. Over a certain range the ratio of repulsive to attractive force increases inversely as the diameter of the particle. A limit to this law of variation is reached when the size of the particle becomes comparable with

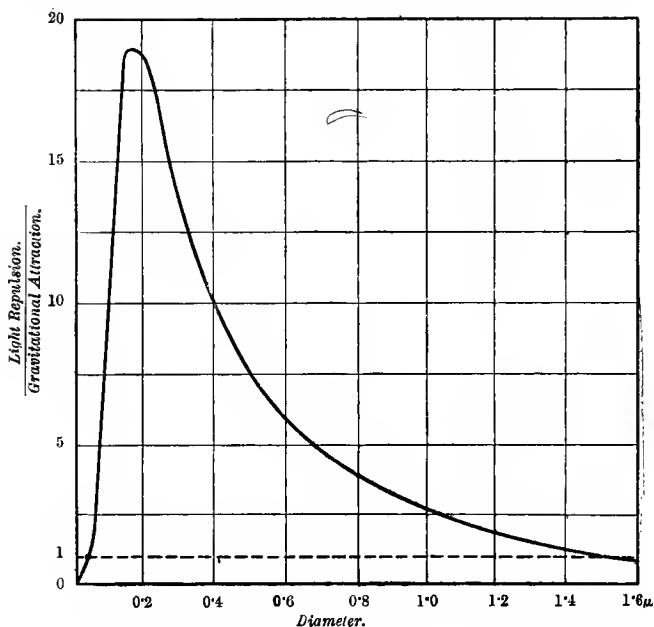


FIG. 46.—VARIATION OF LIGHT-REPUSSION WITH SIZE OF PARTICLE. (Schwarzschild.)

the wave-length of maximum energy in the sun's spectrum. Diffraction effects then come in. The particles no longer absorb or reflect in proportion to their sectional area. Schwarzschild has corrected for this effect. His results are shown in Fig. 46; the material being taken of the density of water, and totally reflecting. At a diameter of 1.5μ the two forces balance.

At 0.16μ (circumference equal to wave-length) the ratio is at its maximum value of 19. There is a balance once more at 0.05μ , or one-tenth λ ; and for particles smaller than this gravity once more preponderates. The maximum ratio of 19 will be reduced to 9.5 if the particle is composed of completely absorbing material. Arrhenius gives reasons for supposing the presence of particles with a density as low as 0.1, in which case the ratio may rise to 40 or more. These high ratios correspond to the nearly straight tails pointing from the sun, which consist of particles streaming away at high speeds from the nucleus—on their way out of the solar system altogether, under the extreme repulsive influence of the solar rays.

CHAPTER X.

SHORT ELECTRIC WAVES AND LONG HEAT WAVES.

1. It is just over 30 years ago since Langley commenced his great research on the infra-red solar spectrum. At that time the spectrum appeared to be limited on the side of greater wave-lengths by a band at $\lambda=1\mu$. Such was the moderate degree of success achieved since 1800, when Herschel showed by the simple heating effect that the solar spectrum extends, on the side of the red, beyond the visual range. Langley greatly improved the sensibility of the receiver of radiation by the invention of the bolometer. He introduced accuracy into the determination of wave-lengths by the use of a reflecting diffraction grating, designed of short focus in order to produce a "hot spectrum." He avoided absorption in his spectro-scope by the use of a train of rock salt lenses and prisms; re-polishing surfaces, sometimes after only a few hours' use, to overcome the rapid deteriorating effect of moisture. One result of his work was an accurate map of the spectrum as far as 5.3μ , and an extension of the known range to 15μ , or possibly further.

**Historical
Outline.**

Langley.

It was in 1887, when Langley's researches were practically completed, that Hertz made his discovery of electric waves. It is hardly necessary to emphasise the immense significance of this event. Clerk Maxwell had early in the previous decade enunciated his theory that light and heat consist of electromagnetic waves. The waves of Hertz, produced by direct electrical means, had a wave-length of not less than some 60 cms. In succession Lodge, Righi, Lebedew, Lampa, and Chunder Bose reduced the wave-length of the rays emitted by the electrical oscillator down to a limit of 4 mm. By the use of these short waves the verification of the analogy of behaviour of these rays and visible rays, begun by Hertz, was carried into greater detail; the existence of the more recondite phenomena, such as double refraction in crystals and rotatory

polarisation, was established. The whole range of wave-lengths, from infinity down to a few millimetres, had been annexed to the domain of ether waves.

Rubens.

2. Much work remained to be done to unify the subject. Maxwell's theory involved the correlation of the electrical and optical properties of bodies. It is a far cry from waves evident to the eye ($\lambda=0.4\mu$ to 0.8μ) to waves of a centimetre in length; from frequencies of billions per second to those of millions per second, and from those downwards to the all-important limiting case of steady electric fields, under which electrical conductivities and dielectric constants are measured. The work of Prof. Heinrich Rubens, of Berlin, has served splendidly in bridging the gap referred to, and in solving outstanding problems of the Maxwellian theory. Langley replaced the Melloni thermopile by the much more sensitive and swiftly working bolometer: Rubens, on the other hand, has taken up and improved the thermopile, producing a linear type which possesses qualities equal, or, under appropriate conditions, even superior to those of the bolometer. He has worked out a method of generating homogeneous infra-red radiation of great wave-length ("reststrahlen" or "residual rays") by utilising the property of selective metallic reflection possessed by certain crystalline bodies. Comparatively recently (1911), in conjunction with Prof. R. W. Wood, he has developed another method—that of focal isolation—whereby a fairly homogeneous radiation of approximately $\frac{1}{3}$ mm. wave-length has been obtained. These researches of Rubens cover a period of close on 20 years, and are actively in progress at the present moment. His recently published results show no signs of diminished value or interest.

With regard to radiation on the immediate ultra-violet side of the visible spectrum, the range known is not very large. Great difficulties are encountered owing to absorption by the media employed. Quartz prisms begin to absorb strongly at 0.18μ . With fluorite it is possible to go as far as 0.12μ . By the use of the concave reflecting grating, Lyman has succeeded in getting up to 0.103μ . At these short wave-lengths, the source of the radiation and the optical apparatus have to be enclosed in vacuo, since beyond 0.2μ the air itself becomes opaque.

Thus at present the range of etheric waves is from $\lambda=0.1\mu$ to $\lambda=\alpha$, with an unbridged gap of nearly four octaves extending

from $\lambda = \frac{1}{3}$ mm. to $\lambda = 4$ mm. This is best represented diagrammatically in octaves according to the method employed by Guillaume in 1899. The diagram of Fig. 47 is drawn to represent the known spectrum up to the end of 1911.

A remarkable series of researches dates from June, 1912, when Laue, Friedrich and Knipping announced the observation of interference phenomena in the case of the reflection of X-rays by crystals. The experiments, continued by W. H. and W. L. Bragg, C. G. Barkla and others, point to the existence not only of a continuous spectrum over a wide range, but of homogeneous radiations of considerable intensity, in fact of spectral lines. The wave-length of these homogeneous radiations is of the order 10^{-8} to 10^{-9} cm. The uniform arrangement of molecules in a crystal furnishes a space diffraction grating of the requisite

**Wave-length
of X-Rays.**

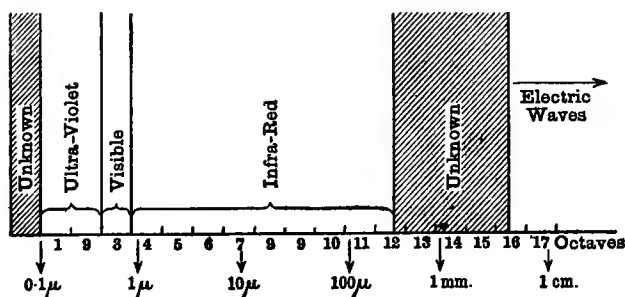


FIG. 47.—SPECTRUM OF ETHER WAVES.

dimensions for sifting out waves of such short wave-lengths. The phenomena have an added value in that they appear likely to open a supply of information of the greatest value in regard to the spacial arrangement of molecules in crystals.

THE WORK OF RUBENS.

3. Maxwell singled out two relationships which follow from the electromagnetic theory of light. The first is that the square of the refractive index for infinite wave-length is equal to the specific inductive capacity K, or

**Two Conse-
quences of
Maxwell's
Theory.**

$$n_{\infty}^2 = K, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The second connects the transparency of a body with its electrical conductivity. Perfect conductors should be perfect reflectors of radiation, and consequently opaque. The theory is best expressed in Drude's equation—

$$(100-R)\sqrt{K} = \frac{36.5}{\sqrt{\lambda}}, \quad (2)$$

R denoting the percentage of reflected light of wave-length λ (microns); and K the electrical conductivity, measured as the reciprocal of the resistance of a column of 1 sq. mm. cross-section and 1 metre length. Thus $(100-R)$ denotes the intensity of the radiation that penetrates into the substance; and the electromagnetic theory states that this is, for a given wave-length, inversely proportional to the square root of the electrical conductivity.

These two relations can be tested by the data of experiment. It is well to bear in mind the manner in which Maxwell himself regarded them. In respect of the former he selected the case of paraffin wax, the only substance for which the dielectric constant was at that time accurately known. He remarked that that value of n must be selected which corresponds to waves of the longest periods, as K is only determined by very slow processes; and extrapolating (formula not stated) for n_∞ from the value of n of melted paraffin for visible rays, arrived at the number 2.02 for n_∞^2 ; which is not greatly different from the value 1.975 found for K . But he remarked that "our theories of the structure of bodies must be much improved before we can deduce their optical from their electrical properties." As regards the opacity of metals, Maxwell noted the greater transparency of gold foil than according to calculation, so far as this calculation was possible with the data then available, and commented again on the desirability of a greater knowledge of molecular structure. Here we have the key to much of the work undertaken by Rubens. He set before himself the problem of investigating the dispersion—that is, the relation between refractive index and wave-length—of as great a number of bodies as possible. This involved the extension of the range of the spectrum on the infra-red side, and, moreover, the production of homogeneous long-waved radiations of sufficient intensity to allow their properties to be ascertained.

Since the time of Maxwell the electron has emerged, and won an outstanding position in electrical theory. In it we have to a large extent that knowledge of molecular structure whose desirability Maxwell foresaw.

Below is given some account of the valuable additions to our knowledge which have been contributed by Rubens, and of their relation to electromagnetic theory.

4. *Measurements of Dispersion.*—The passage of radiation through any substance is affected by the presence of the contained electrons. These may be bound to the molecules, any displacement being accompanied by a restoring force increasing with the displacement; or they may be able to move freely in the interstices of the substance. In insulating media the electrons are almost entirely of the former class; in metals the free electrons predominate, though not to the entire exclusion of the others. The problem of the effect on the body of an alternating electric force is similar to that of forced vibrations in a mechanical system, and the resulting relation between the refractive index and the wave-length is expressed in the Ketteler-Helmholtz dispersion formula

**Rubens' Tests
of Eqn. (1).**

$$n^2 = b^2 + \frac{M_1}{\lambda^2 - \lambda_1^2} + \frac{M_2}{\lambda^2 - \lambda_2^2} + \dots \quad (3)$$

Here λ_1 , λ_2 , &c., represent the wave-lengths corresponding to the natural periods of the bound electrons, whose existence gives rise to the presence of absorption bands in the transmission spectrum; b , M_1 , M_2 , &c., are constants depending on the substance. When the wave-length λ of the incident radiation is very great compared with λ_1 , &c., all terms of the

form $\frac{M}{\lambda^2 - \lambda_m^2}$ vanish, and we have $n_\infty^2 = b^2$, so that by (1) b^2 should be equal to K , the dielectric constant. It is clear, therefore, that to deduce K by the aid of equation (3) it is necessary to know all the free periods for the region of the spectrum in which n can be determined. Neglecting more distant free periods that may exist, the general formula may be simplified, without much sacrifice of accuracy, so as to contain only one or two terms beyond the constant b^2 .

The case of the ordinary ray in quartz was investigated with

great care, and found to be well represented by taking three terms. The constants were as follows :—

$$\begin{array}{lll}
 & M_1 = 0.0106 & \lambda_1 = 0.106\mu \text{ (ultra-violet),} \\
 b^2 = 4.578 & M_2 = 44.224 & \lambda_2 = 8.84\mu \text{ (infra-red),} \\
 & M_3 = 713.55 & \lambda_3 = 20.75\mu \text{ (infra-red).}
 \end{array}$$

The dielectric constant of quartz is found by experiment to be 4.58, which agrees remarkably well with b^2 .

In many other cases, including sylvine, flint glass, carbon bisulphide, and benzene, the agreement between K and the value of b^2 obtained by taking account of only two free periods is extremely good.

The case of water is of almost classic interest. The refractive index for sodium light is 1.33, the square of which is 1.78; the dielectric constant is 80. The inequality between these numbers is no small one: on the resonance theory its removal involves the presence of absorption bands in the infra-red—which would correspond with the well-known athermancy of water to dark heat rays. Even at $\lambda = 82.3\mu$ Rubens finds the refractive index of water to be no greater than 1.41. For electric waves of 5 cm. length, however, the refracting power has fully attained the high value corresponding with $n^2 = K$ (see Table III.). The transition appears to occur within the now comparatively narrow band of unexplored radiation separating the “heat” and “electrical” rays.

Production of Infra-red Rays.

1. Selective Reflection.

5. *Methods of Production of Homogeneous Infra-red Rays.*—

(i.) *By Selective Reflection.*—The values of λ_1 , λ_2 , &c., in the dispersion formula represent the wave-lengths for which resonance occurs. A very considerable fraction of the incident light of these wave-lengths is reflected. This fact of selective reflection by crystalline bodies, so great as to resemble metallic reflection, has been seized by Rubens and applied with very fruitful results. By making use of reflection at three or four polished plane surfaces in succession the proportion of the selectively reflected rays remaining is still great, whilst the intensity of all other radiations is reduced practically to annihilation. The wave-length of the residual rays may be determined by the aid of the diffraction grating; or, better still, by the interferometer, which is found to require a less intense beam than the grating. These purified rays are of sufficient

intensity to allow of the study of their properties. The number of substances found suitable for their production is continually increasing, and now includes quartz (8.84μ), fluorite (24.4μ), rock salt (51.2μ), sylvine (63.4μ), potassium bromide (82.3μ), and potassium iodide (96.4μ).

(ii.) *By Focal Isolation.*—In 1911 Rubens, in conjunction with R. W. Wood, published an account of a successful attempt at extending the known infra-red spectrum by a new method involving selective refraction through quartz lenses. The resulting rays practically form a narrow band in the spectrum, which, with an incandescent Welsbach mantle as source, was found to be at 108μ ; whilst with a quartz mercury lamp the band was at 314μ .

2. Focal Isolation.

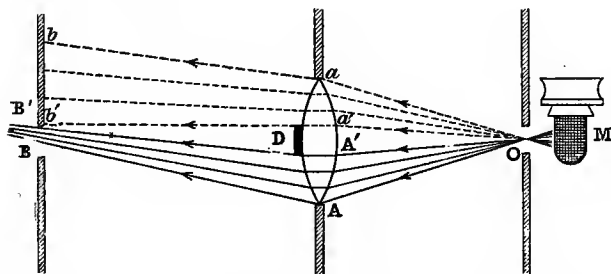


FIG. 48.—FOCAL ISOLATION OF INFRA-RED RAYS. (Rubens and Wood.)

The mode of separation of the long from the short waves will be seen with the aid of the diagram of Fig. 48. A disc *D* of black paper, an inch in diameter, stops all transmission through the central portion of the lens. The shorter waves which the lamp emits, of refractive index 1.43 to 1.53, occupy the region whose limits are represented in the upper half of the diagram by *Oab* and *Oa'b'*. These fail to pass through the aperture in the screen *E*. Now quartz strongly absorbs the longer waves within the range of refractive index 1.5 to 2.14. For still greater wave-lengths the refractive index rises to a maximum of 2.19, after which it falls to the limiting value of 2.14. These long waves, being more strongly refracted, pass through the aperture, as shown by the bounding rays *OA'B'*, *OAB* in the lower half of figure. They then fall on a second and

similar lens (not shown), which serves to complete the separation, and to condense the rays on the measuring instrument, which was a radiomicrometer. Practically no waves shorter than 80μ succeed in getting through. The energy curve is found to rise rapidly on the side of shorter wave-lengths, showing a maximum intensity at 108μ , and falling off more slowly towards the greater wave-lengths. Thus, by taking advantage of the law of dispersion and the selective absorptive power of quartz, rays approximately homogeneous, of wave-length 108μ , were obtained.

It seemed hopeless, in view of the fact that the intensity of the radiation emitted by purely thermal radiators falls off inversely as the fourth power of wave-length, to expect to extend the spectrum further whilst employing such sources. Rubens and Baeyer therefore had recourse to electro-luminescence, replacing the incandescent Welsbach mantle by the quartz mercury lamp; and succeeded in producing rays of wave-length 314μ , or 0.314 mm. These are the longest heat rays hitherto produced.

Rubens'
Tests of
Eqn. (2).

6. *Optical Properties and Electrical Conductivity.*—Rubens' work in reconciling observation with the demands of theory has met with remarkable success in regard to the relations between reflective power and electrical conductivity. Phenomena such as the great transparency of gold-foil to green light involve, on the electronic hypothesis, the presence in the metal not only of the free electrons which account for its conductivity, but of electrons bound to atoms and possessing natural periods of vibration. Drude's equation (2) is built up on the assumption of the presence of the former only. Rubens has tested its applicability to metals by experiments made with residual rays, from which it would appear that for wave-lengths greater than 4μ the disturbing effect of bound electrons rapidly falls off. The emissive powers of thirty-seven metals or alloys were determined, with reference to a black body as standard, for the radiation of wave-length 25.5μ separated by successive reflections from fluorite. The values obtained in the case of pure metals are shown in Table I.

The high value for aluminium is attributable to the difficulty of freeing the surface from oxide. The case of bismuth forms a genuine exception, to be classed with its abnormal behaviour

Table I.—*Emissive Power and Electrical Conductivity* $\lambda=25.5\mu$.

Metal.	\sqrt{K} .	Emissive power (100-R).	(100-R) . \sqrt{K} .
Silver.....	6.26	1.13	7.07
Copper	5.70	1.17	6.67
Gold	5.21	1.56	8.10
Aluminium	4.52	1.97	8.91
Zinc	3.19	2.27	7.24
Cadmium	2.86	2.55	7.29
Platinum	2.44	2.82	6.88
Nickel	2.29	3.20	7.33
Tin.....	2.24	3.27	7.32
Palladium	2.11	3.58	7.53
Mercury	0.957	7.66	7.33
Bismuth	0.716	25.6	18.3

The numbers in the last column should, according to (2), be constant, supposing the effect of bound electrons to be negligible.

in regard to the Hall effect, and to variation of resistance in a magnetic field; all being connected, in Rubens' view, with the crystalline structure of the metal. The mean value of $(100-R)\sqrt{K}$ for the remainder comes to 7.27, which agrees remarkably with the theoretical value $\frac{36.5}{\sqrt{25.5}}=7.23$. The question of the verification of Maxwell's theory as regards good conductors may well be regarded as closed.

The case of electrolytes is interesting. Whereas their electrical conductivity is comparatively great, many aqueous salt solutions are practically transparent to visible radiations. This is explicable by the complete absence of free electrons, and of natural free periods agreeing with those of light. For the long infra-red, as well as for electric waves, the same solutions are practically opaque. It is interesting to compare with this the behaviour of iron under the influence of alternating magnetic force. The ultimate particles of iron are able to respond to alternations of magnetic force of millions per second, but fail to do so in the case of the far more rapid alternations (of billions per sec.) which occur in light; so that for the latter, iron, like other substances, possesses a permeability which is practically unity.

Resonance.

7. *Resonators and Polarising Gratings for Heat Waves.*—There is space for only the briefest reference to Rubens' interesting experiments on these points. The facts of electrical resonance, first discovered by Hertz, are now very familiar in their application to wireless telegraphy. On the electromagnetic theory, infra-red rays should produce an exactly similar resonance. The resonators must be of smaller dimensions, but for the longer infra-red waves the difficulties of construction are not insuperable. Rubens constructed a series of resonators by ruling two sets of lines, at right angles to each other, on a silvered glass plate. The silver was thus cut up into a large number of equal parallel linear resonators. A number of plates were prepared, the length of resonator being different in each. Plane-polarised rays, of wave-length 25μ , were allowed to fall on each plate in turn, the plane of polarisation being perpendicular to the length of the resonators. The fraction of radiation transmitted should, in accordance with the conditions of production of stationary vibrations, be least when the silver strips have a length which is an even multiple of a quarter wave-length, greatest when the length is an odd multiple. The results obtained showed a rise and fall in the fraction of light transmitted, according to length of strip, which, if not exactly as expected, was sufficiently satisfactory to establish the existence of the effect in question.

**Polarisation
by Wire
Gratings.**

The polarising effect of wire gratings on infra-red rays has been clearly demonstrated. Gratings of uniformly spaced parallel wires stop electric waves when the electric force is parallel to the wires, allowing considerable transmission when the electric vector is perpendicular. In the general case therefore the effect of the grating is to split the incident beam into two, one reflected and the other transmitted, with planes of polarisation mutually perpendicular. The distinction between a polarising grating and a diffraction grating, it should be pointed out, depends on the ratio of width of grating space to wave-length. If the ratio is large, the apparatus behaves as a diffracting instrument; if small, the diffracting effect loses as the polarising effect gains in importance.

Gratings of wire of various metals—silver, copper, &c.—were constructed with space widths from 10μ to 60μ . With visual rays the polarisation observed in the central (undiffracted)

image was small, and, moreover, not of the character shown by electric waves—*Hertzian* polarisation, as it may be termed, was absent. As the wave-length increased, the fraction of the transmitted light polarised in the plane of the wires was found to increase more and more; and in the case of the longest waves (314μ) the Hertzian polarisation for the above gratings was complete. Rubens, indeed, states that a wire grating is a much more complete and convenient polariser for long infra-red rays than the usual reflecting surface. With a grating of quartz threads no such effects were found.

In accordance with the connection between absorptive and emissive powers, it follows that a conducting grating, if heated, should emit plane polarised radiation, just as does a heated tourmaline. Rubens obtained a specially woven Auer mantle, with strands in one direction only, and succeeded in showing that the long infra-red rays emitted by it at incandescence were distinctly polarised, the plane of polarisation being perpendicular to the strands.

8. *The Reflecting and Absorbing Powers of Substances for Infra-red Waves.*—The longest heat waves (314μ) of Rubens are distant only three and a half octaves from the shortest electric waves ($4,000\mu$), whilst they are removed nine octaves from red light. Their properties in regard to absorption, reflection and refraction are often nearer those of Hertzian than of visual rays. Table II. summarises Rubens' results for some important substances whose behaviour as regards electric waves and visual rays is well known; the transmissibility for electric waves being, in fact, fairly high in all the cases shown, with the exception of water.

**Absorption
of Extreme
Infra-red
Radiations.**

Table II.—*Transparency of Bodies for Long Infra-red Radiations.*

Substance.	Thickness of plate (mm.).	Percentage transmitted.	
		$\lambda = 108\mu$.	$\lambda = 314\mu$.
Paraffin wax	3.0	57.0	85.5
Ebonite	0.4	39.0	65.3
Glass	0.18	2.1	25.9
Mica	0.055	16.6	55.0
Water	0.038	20.0	39.8
Black paper	0.11	33.5	79.0
Black cardboard	0.38	2.1	36.7

The great transparency of lampblack for these long waves is also of interest. Films of smoke so thick that the sun could not be seen through them were found to transmit 0.5 per cent. at 2μ , 16 per cent. at 6μ , 76 per cent. at 26μ , 91.5 per cent. at 108μ . For very long waves Rubens and Wood coated the surface of their receiving thermo-couples with a thin film of water-glass in place of the usual smoke film, and found the sensibility to be decidedly increased thereby.

EXPERIMENTS ON SHORT ELECTRIC WAVES.

Production of Short Electric Waves.

9. The production of extremely long electric waves, hundreds of feet in length, is a matter to-day of engineering practice. The waves which Hertz largely confined his attention to had a wave-length of 60 cm. By reduction of the size of oscillator shorter waves may be generated, but on account of technical difficulties a practical limit appears to be reached at a wave-length of about half a centimetre. Righi experimented with waves 2.5 cm. long. Lebedew succeeded in obtaining waves of 6 mm. length; and Lampa, with a similar oscillator, reduced the value to 4 mm. Bose, in this country, worked with waves down to 6 mm. length. The difficulties of exact measurements of absorption, &c., appear to be great in the case of the shortest waves.

Lebedew.

Lebedew's oscillator consisted of two platinum rods, *ss*, 1.3 mm. long and $\frac{1}{2}$ mm. thick, separated by a distance of 0.02 mm., and immersed in paraffin oil. The platinum rods were sealed at the ends of glass tubes, the charges being conveyed by the wires *ww*, separated by air-gaps from *ss*. The receiver consisted of two platinum rods 3 mm. long, the heating effect in which actuated a thermo-couple connected to a delicate galvanometer. Amongst many demonstrations of the analogy of behaviour of his rays ($\lambda=6$ mm.) and visible rays was the discovery of the double refraction of crystalline sulphur, the principal indices being measured at 2.25 and 2.00, which agree well with the values 2.18 and 1.95 obtained by taking the square root of Boltzmann's values for the specific inductive capacities in the same directions.

Lampa.

Lampa's receiver was a coherer. The waves used were of lengths 4, 6 and 8 mm. respectively. He noted the greatly reduced sensibility of the coherer for the 4 mm. waves. His

most interesting measurements were on the refractive indices of water and alcohol, the method of deviation by a prism being employed. In the case of water the angle of the prism had to be limited to 4 deg., owing to its great absorbing power; for absolute alcohol a refracting angle of $16\frac{1}{2}$ deg. was employed. His results are quoted in Table III.

Bose worked with waves from 0.6 up to 2.5 cm. in length, produced by an oscillator of the Lodge type. Using, for example, a central (insulated) platinum sphere of 7.8 mm. diameter, separated by air-gaps each 0.6 mm. from two platinum beads of 3 mm. diameter, waves of 1.85 cm. length were obtained. The receiver was a coherer consisting of a row of spiral springs in contact, placed in circuit with a dead-beat

Bose.

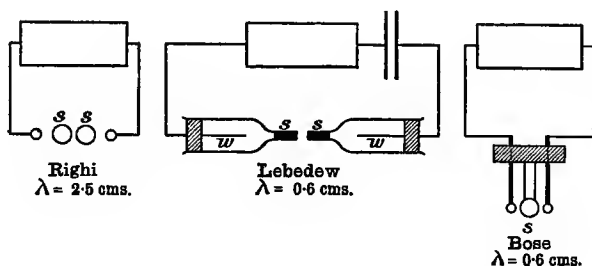


FIG. 49.—SHORT ELECTRIC WAVE TRANSMITTERS.

galvanometer. He employed a cylindrical diffraction grating for his wave-length determinations. This he constructed with strips of tinfoil 3 cm. wide separated by spaces of equal value, the strips being pasted on a thin sheet of ebonite. The measurements appear to possess considerable accuracy. He found the refractive index of crown glass, by measurements of the critical angle, to be 2.04.

Reference may here be made to Cole's experiments on the velocity of wire-guided electric waves, of lengths 250 cm. to 600 cm., through air, water and alcohol respectively, whence the refractive indices of alcohol and water were found. Experiments with waves of 5 cm. length were also made, the refractive index being deduced in this case from the reflecting power by application of Fresnel's formula.

***n* for Water and Alcohol.**

10. Values of the refractive indices of water and alcohol for various wave-lengths are collected in Table III. It appears that the discrepancy between n^2 and K steadily disappears in the case of alcohol as the wave-length increases. The case of water is curious. The limiting value n_α appears to be practically attained at $\lambda=5$ cm., whereas at $\lambda=82\mu$ the refractive index is only slightly greater than the value for light rays. According to the experiments of Baeyer and Wood the behaviour of water in regard to waves of length $\lambda=314\mu$ indicates that the refractive index is still on the low side. The intervening values, apparently, remain to be found in just the narrow spectral region as yet unexplored.

Table III.—*Refractive Indices of Alcohol and Water at Various Wave-lengths.*

Alcohol : $K=25$.				Water : $K=80$.			
λ .	n .	n^2 .	Authority.	λ .	n .	n^2 .	Authority.
0.59μ	1.37	1.88	...	0.59μ	1.33	1.78	...
108μ	1.4	1.96	Rubens	82μ	1.41	1.98	Rubens
4 mm.	2.24	5.02	Lampa	5 cm.	8.85	78.0	Cole
5 cm.	3.2	10.24	Cole	60 cm.	8.7	75.6	Drude
60 cm.	4.74	22.5	Drude	600 cm.	8.9	79.2	Cole
259 cm	5.24	27.4	Cole

CHAPTER XI.

FREE ELECTRONS IN METALS.

**The
Electron.**

1. When Sir J. J. Thomson in 1897 measured the ratio of charge to mass in the case of the negatively electrified particles constituting the cathode rays, the mystery of the "fourth state of matter" was well in process of elucidation. A year or two later the value of the charge was shown to be the same as that carried by each hydrogen atom in the electrolysis of water. The evaluation of the mass of the particle was thus made possible. This mass turned out to be the smallest ever observed, being only about one-seventeen-hundredth part of the mass of an atom of hydrogen. Now an electric charge possesses inertia in virtue of its charge, and there is strong experimental evidence in support of the view that the mass of the cathode ray particle is wholly due to the charge. The diameter of the particle, on this basis, is about 10^{-13} cm., exceedingly small compared with the corresponding quantity (10^{-8} cm.) for the atom. Such particles are met with also in connection with phenomena outside the vacuum tube. In every case they appear to be of one kind, no matter what chemical substance they are drawn from. The value of the charge as given originally by Prof. Thomson is 3.4×10^{-10} electrostatic units, though recent determinations point to a higher value of about 4.65×10^{-10} E.S. For these negative units which enter into the composition of all atoms the term electron is here used.

The conception of the electron was speedily applied to explain various phenomena, not only electrical but also thermal, and even optical, occurring in metals.

2. Riecke and Drude assumed the presence in metals of charged particles of several kinds, capable of travelling from one point to another of a metal under an applied electric force. Sir J. J. Thomson showed that the same results could be deduced without postulating any mobile charged particle save the electron. The smallest positive charge obtainable is associated

**Ions in
Metals.**

with the atom, and though inter-diffusion of two metals in contact (in the solid state) has been observed, there is no evidence of the transport of matter in the conduction of electricity through metals, though this effect has often been looked for. Great gain in simplicity is secured by postulating only one moving charge, namely the electron, and this view is now commonly adopted.

Free Electrons.

3. Electrons may occur bound to the positive residue of the atom, as in insulators; or free, in the sense of being practically out of range of other charges of either sign. The former manifest their presence in metals to a slight extent, accounting for selective transmission and reflection of light, as in gold leaf. They move in atomic orbits, and are specially susceptible to the influence of light waves of their own natural period. The free electrons wander in the interstices between the atoms, with which they are continually in collision. Preciseness is given to the notion by the assumption, advanced both by Drude and Thomson, that their movements of translation are exactly similar to those of the particles of a perfect gas, and that the mean kinetic energy of translation of an electron is the same as that of a gas molecule at the temperature of the metal. This quantity of energy is proportional to the absolute temperature θ , and is generally denoted by $\alpha\theta$; α being a universal constant, which has recently been extended to embrace molecules in the liquid and solid states. On the basis, then, that $\frac{1}{2}mv^2$ is to be the same for the electron as for a gas molecule, we may calculate the value of v the root mean square value of the velocity of the free electron. In the case of hydrogen the velocity at 0°C. is 1.7×10^5 cms. per sec., therefore the speed of the electron at 0°C. is to be taken as 58 times as great, say 10^7 cms. per sec.

The number present per unit volume would appear not to vary greatly from one metal to another, and to be about equal to the number of atoms. Now the number of atoms per c.c. in silver is estimated at 7.3×10^{22} . As hydrogen at standard temperature and pressure is estimated to have 3.15×10^{19} molecules per c.c., we see that the pressure due to the electrons in silver should be of the order 2,300 atmospheres.

The constitution of the metal may be pictured as in the diagram opposite, in which the large discs represent atoms, the small ones electrons. We have to imagine minute particles

of electricity possessing inertia, moving in the spaces of an open network of atoms, in various directions and with various speeds, and sometimes breaking through the surface into the region outside.

With the aid of this conception of the free electron it is possible to unify such diverse phenomena as electrical conduction, conduction of heat, and the emission of radiant heat and light.

4. *Electric Conduction in a Metal.*—When an electric force or potential gradient is applied to a metal, the free electrons will drift in the direction opposite (their charge being negative) to that of the applied field. If u be the speed of drift, n the number of free electrons per c.c., e the electronic charge, the current-density will be $i = neu$. The value of u may be found in terms of the electric force X , the mean speed v of the elec-

**Electric
Conduction.**

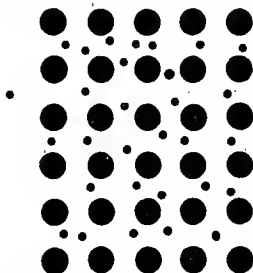


FIG. 50.—DIAGRAMMATIC REPRESENTATION OF ATOMS OF A METAL WITH INTERSPERSED ELECTRONS.

trons at the temperature of the metal, the mean free path λ of the electron between successive collisions with atoms, and e and m . Assuming, as we may, that the change of speed of the electron due to the electric field is small compared with v , we have $t = \lambda/v$ for the interval of time between two collisions. The force acting on the electron in its free path is eX , and its acceleration is therefore $\frac{eX}{m}$. At the end of the time t its

velocity is $\frac{eX}{m} \cdot t$, therefore the mean velocity is $\frac{1}{2} \frac{eX}{m} \cdot t$, or $u = \frac{1}{2} \frac{eX}{m} \cdot \frac{\lambda}{v}$; so that $i = ne \cdot \frac{1}{2} \frac{eX \lambda}{m v} = \frac{ne^2 \lambda v}{4\pi\theta} \cdot X$. The current is

thus proportional to X ; which expresses Ohm's law. The electric conductivity is defined by the equation $i = \sigma \cdot X$. Therefore

$$\sigma = \frac{ne^2\lambda v}{4a\theta} \quad . \quad . \quad (\text{electrical conductivity}) \quad . \quad . \quad (1)$$

The product $n\lambda$ is the only variable part of this expression at any particular temperature. The difference in conductivity between one metal and another is thus to be attributed to differences in n or λ or both. Now considerations based on the Peltier effect lead to the conclusion that the values of n do not differ greatly from one metal to another, so that on the present view the differences in conductivity depend mainly on differences in the electronic mean free paths.

As regards the effect of temperature, we have $v \propto \theta^{\frac{1}{2}}$; and the Thomson effect leads to the conclusion that n varies very nearly as $\theta^{\frac{1}{2}}$. Now since for a pure metal σ is found experimentally to be inversely proportional to θ , it follows that λ varies inversely as θ . Here we encounter one of the difficulties in the way of the theory of free electrons. For if λ is determined by the mean distance apart of the atoms of the metal, it would appear as though it should vary only very slowly with change of temperature, at a rate in fact equal to the coefficient of linear expansion. Possibly, it has been suggested, the mean free path is determined by the size of a *cluster* of atoms, such clusters going in their turn to the building-up of the crystals of which metals are composed. These clusters must be supposed to break up with temperature in the rapid manner required.

Joule's law of heating may be readily deduced. The heat developed is the sum of the increments of kinetic energy acquired by the electrons during their free-path motion in the electric field, and this can be shown to be i^2/σ per unit volume.

The small conducting power of the salts of a metal is attributable to the small number of free electrons present. For the metal being electro-positive has parted with one or more electrons to the electro-negative radical; its power of parting with another electron is thus effectively reduced.

Thermal Conductivity.

5. *Thermal Conductivity and its Relation to Electrical Conductivity.*—Let us consider a rod of metal hotter at one end than the other. According to our theory the distribution of

free electrons and their mean velocity will show the same variations from section to section as in an equal column of gas heated in the same manner. The number crossing any section from the hot side to the cold will be the same as from the cold side to the hot side, the greater mean speed on the hot side being just compensated by the greater number per unit volume on the cold side. There will be no electric current, in other words. But the kinetic energy transferred over the section from hot to cold will exceed that passing in the reverse direction. The heat-crossing unit area under unit temperature gradient will thus be given by the same expression that applies to a gas, namely,

$$k = \frac{1}{3} n \lambda v a \quad \dots \text{ (thermal conductivity), } \quad (2)$$

Attributing the transfer of heat entirely to the movement of electrons, the thermal conductivity of the metal will be denoted by k in the above formula. At any chosen temperature it appears on this supposition that the value of the thermal conductivity is determined by the product $n\lambda$, just as in the case of the electrical conductivity. Taking the ratio of the two conductivities, we have

Ratio $\frac{k}{\sigma}$

$$\frac{k}{\sigma} = \frac{4}{3} \frac{\alpha^2}{e^2} \cdot \theta. \quad \dots \quad (3)$$

As α and e are constants, this means that at any chosen temperature the ratio of the thermal to the electrical conductivity is independent of the nature of the metal; and, furthermore, that the ratio varies exactly in proportion to the absolute temperature. The ratio α/e may easily be calculated without any of the uncertainty that attaches to the determination of either α or e by itself. Its value is 12,800; hence at 0°C . we get $k/\sigma = 6.3 \times 10^{10}$ in absolute measure. The agreement between theory and experiment, though far from exact, is yet remarkable, and serves, on the whole, as a signal vindication of the theory. Researches, particularly those of Jäger and Diesselhorst between 18°C . and 100°C ., and of Lees over the range -170°C . to $+30^\circ\text{C}$., afford ample evidence of this. To choose a few examples from the results obtained by Prof. Lees: the ratio of the conductivities at 0°C . is for copper 6.28, for aluminium 5.70, for silver 6.36, each number to be multiplied by 10^{10} . In the case of alloys the ratio is distinctly higher

(10.3×10^{10} for manganin at $0^\circ\text{C}.$); but for such combinations there may enter thermoelectric effects such as Lord Rayleigh has suggested, which would call for a supplementing of the theory.

Wiedemann and Franz had, over half a century ago, and Forbes even earlier, enunciated as an empirical law the equality of the ratio of the thermal and electrical conductivities of all metals. They imagined this ratio, however, to be also independent of temperature. It is of historical interest to recall the many experiments made with a view of demonstrating the anticipated variation of thermal conductivity in accordance with the well-known law of variation of the electrical conductivity; and to observe what contradictory results were obtained, sometimes a negative temperature coefficient, sometimes a positive coefficient, being suggested by experiments on the same metal. Prof. Lees' experiments over the wide range of $200^\circ\text{C}.$ show how small comparatively the changes really are. Most pure metals show a slight fall of thermal conductivity with rise of temperature. For copper, over the full range mentioned, the fall is 18 per cent.; for silver 3 per cent. In the case of alloys there is generally an increase of conductivity with increase of temperature, the change being much larger than for pure metals.

It may be remarked here that such divergencies from theory as those quoted will be met with in all phenomena in the domain of the electron theory as applied to metals, whenever the strict quantitative test is applied. The phenomena are not as simple as this theory indicates.

The question arises of the reasonableness of neglecting the part played by the atoms themselves in the conduction of heat. That the atoms, or molecules, do contribute to some extent is shown by the fact that when the number of free electrons is negligibly small, as in insulators, the thermal conductivity is quite measurable. The values show, however, how small a share is taken as a rule by the atoms. The thermal conductivity of paraffin wax, for example, is only about one-seventeen-hundredth that of copper. On the other hand we have cases such as quartz, an electrical insulator of the highest class, of which the thermal conductivity along the optic axis is 0.029, a value exceeding that of some metals.

6. *The Emission of Electrons from Metals.*—The conception of a metal as an open network in the meshes of which electrons flit to and fro prepares one for the fact that under various circumstances electrons are emitted by metals. **Electronic Emission.**

The phenomenon of radio-activity is one whose explanation lies outside the present considerations; the rate of emission of electrons, or β -rays as they are in this case termed, being, so far as is known, quite independent of temperature or any other physical condition.

Electrons are also emitted by metals under the influence of light, of cathode-rays, of α -rays, of γ -rays, and of X-rays. Whether the effect is on the free electron in these cases is perhaps more than doubtful. There is an alternative explanation, namely, in the explosion of a molecule in which there is an electronic orbit. If energy be imparted to the molecule by one of the above-mentioned agents, it is conceivable that the velocity of the revolving electron might rise to a point which would force it to break loose from its orbit. If so, the velocity of the escaping electron might be expected to be, for any particular metal, independent of the intensity of the incident radiation, though different for different metals. Experimental data are, however, not conclusively in favour of the explosion theory. In the case of the photo-electric effect, the velocity of the emitted electrons is about 5×10^7 cms./sec., and appears to be independent of the nature of the metal; it is also independent of the intensity of the radiation, but increases as the wave-length of the latter decreases. With X-rays the velocity is 7×10^9 cms./sec., varying but little from one metal to another, though distinctly dependent on the hardness of the rays. The secondary cathode-rays due to the incidence of γ -rays leave with the great speed of 2.6×10^{10} cms./sec., a value again apparently independent of the nature of the metal. In the case of these agents the power of ejection may be attributed to the electric force associated with them—for all three agree in being transverse electromagnetic disturbances in the ether. In harmony with this theoretical inference is the fact that electrons are only ejected when the conditions are such that the electric force in the incident beam has a considerable component perpendicular to the surface of the metal. Thus in the case of light, as Elster and Geitel have shown, the effect is very small when the plane

of polarisation coincides with the plane of incidence; and when these planes are perpendicular to one another the photo-electric effect is almost vanishingly small for angles of incidence approaching zero on the one side or a right angle on the other, reaching a maximum at an angle of incidence of about 60° .

Negative Thermions.

No doubt holds, however, as to the effect of high temperature on the free electrons in a metal. Some of these particles near the surface will possess, in accordance with the law of distribution of velocities in a gas, a speed sufficient to carry them through the bounding surface of the metal into the surrounding space. But this escape of electrons, unlike the escape of gas molecules, means the escape of electricity, the metal being thus left positively charged. The loss of electrons in an insulated conductor would soon cease owing to the opposing electric force thereby created at the surface of the metal. Even when the metal is uninsulated the escaping electron has to overcome the attractive force of the opposite so-called induced charge; and in order to escape must do an amount of work against the electric attraction. With rise of temperature the number emitted per second per unit area should rapidly increase. Theory assigns the formula

$$i = an\theta^{\frac{1}{2}}e^{-\frac{w}{\beta\theta}} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

for the quantity of negative electricity leaving the metal per unit area in one second: a and β being constants; and w the work required to drag an electron out of the metal; the other quantities being as previously defined. This is the value of the current intensity obtainable from the metal when an electrode is placed opposite, and a P.D. applied between the opposed surfaces sufficient to drive across the intervening space all the electrons emitted. The experiments of O. W. Richardson show very good agreement of observation with theory. As indicated by the formula, the current intensity increases very rapidly with rise of temperature, attaining in the case of an incandescent carbon filament a value of 2 to 3 amperes per square centimetre. The results lead to a value for n , and also for the work w ; the values in the case of platinum working out at $n = 1.3 \times 10^{21}$ per c.c., and for w the equivalent of the work done in moving the charge e through a P.D. of 5.6 volts.

Measurements have been made on the velocities of emission of the electrons; the numbers found are of the value predicted, whilst the law of distribution of the velocities is in accordance with Maxwell's law.

The rate of emission is greatest in the case of the electro-positive elements. For sodium the effect is considerable at a temperature as low as 200°C. Metallic calcium may be raised to temperatures considerably above 1,000°C., and under these conditions the emission far exceeds that of platinum at the same temperature.

That the electricity actually is carried by free electrons was first shown by Sir J. J. Thomson by measuring the maximum distance to which charged particles could escape when a known magnetic field was applied parallel to the surface. Recently G. Owen and Halsall, using the same method, have shown that the proportion of electricity carried from a hot filament of metal in vacuo, otherwise than by electrons, is exceedingly minute, if any.

7. It is necessary to point out that the emission of electrons often accompanies chemical reactions within the heated substance, or between it and the surrounding gas. Pring and Parker ("Phil. Mag." 1912) have shown that the currents obtainable from a heated rod of carbon fall off greatly as the pressure of the surrounding gas is reduced below 1 mm. of mercury, and also with time as the carbon rod became progressively purer.

**Electrical
Effects
Attending
Chemical
Action and
Sputtering**

Again carbon and certain metals exhibit the phenomena of "sputtering," in which fine particles—aggregates apparently of some thousands of molecules—are thrown off from the heated body. Kaye and Harker ("Proc." Roy. Soc., 1912 and 1913) have shown that the sputtered particles may be charged with negative electricity, and that it is thus possible to convey comparatively large currents across the gas separating unequally heated electrodes, even in the absence of any external E.M.F. In one case where concentric cylindrical carbon tubes were maintained, the inner at a temperature of nearly 3,000°C., the outer at about 1,500°C., the current (in air at atmospheric pressure) through an ammeter connected across the electrodes rose to 2½ amperes. They concluded that the part played by free electrons in such experiments, where the surrounding gas is at atmospheric pressure, is comparatively negligible.

In dealing with the emission of electrons from metals it may thus be necessary to allow for departures from the law of emission of free electrons as given in equation (3), owing to the existence of chemical action or of sputtering.

**The
Fleming
Valve.**

8. The emission of electrons from a hot body has some important applications in theory and practice. The Edison effect in glow lamps is an instance of the phenomenon. In the hands of Prof. Fleming this has become the basis of an electric wave detector, the hot filament readily parting with negative electricity to a neighbouring electrode, but refusing to permit a current in the opposite direction. This "unilateral conductivity" enables the apparatus to serve as a rectifier or valve.

**The Hot Lime
Cathode.**

It is interesting to note the fact, of which good use is made in facilitating the discharge in vacuum tubes, that the hot oxides of the alkaline earths copiously emit electrons, the law of increase with temperature being apparently the same as for a metal. By employing a cathode consisting of a platinum strip on which is a speck of lime or baryta, the strip being raised to a bright red heat by an independent electric current, a strong beam of cathode rays may be obtained with a fall of only one to two hundred volts across the tube.

The intensity of the effect in the case of these oxides is surprising. By the same reasoning that was used above to account for the low electrical conductivity of metallic salts, it might have been expected that the rate of emission from the oxides would be less than from the pure metals at the same temperature. The experiments of Horton on calcium and lime have demonstrated the contrary to be undoubtedly the case.

**Solar
Emission
of
Electrons.**

A cosmical application consists in the theory of the emission into space of streams of negative electricity from the sun's surface. Such an emission would leave the sun positively electrified, and the effect would cease. Even then, however, local rises in temperature, such as are believed to occur in sun-spots, would permit the effect to be for a time resumed. It is such streams, entangled by the magnetic lines of the earth's field and diverted to the magnetic poles, which have been invoked to account for the aurora and for sudden disturbances of the terrestrial magnetic elements (*see* Chapter VI.).

This survey of the phenomena associated with the presence of free electrons in metals will be completed in the succeeding chapter.

CHAPTER XII.

FREE ELECTRONS IN METALS (*continued*).

The phenomena of electric and thermal conduction and of the emission of electricity from hot surfaces have been shown to be explicable in terms of a single conception of the nature and properties of electricity in metals. According to this view atoms of negative electricity, or electrons, exist in the interstices of the metal, just like molecules of a perfect gas in their possession of translatory movement and of kinetic energy, but possessing, over and above, the properties of electrically charged particles.

A *theory of radiation* has been worked out by Lorentz which has the merit of unfolding a mechanism of emission of radiant energy by a body. As is well known, Boltzmann has discovered, from thermodynamical considerations, an expression for the total radiation from a full radiator or black body; and Wien another for the law connecting intensity, wave-length and temperature, likewise in the case of a full radiator. The thermodynamical reasoning cannot be carried so far as to determine the form of the spectral energy curve, though given the curve at one temperature, Wien's law asserts that the curve for any other temperature may be drawn. It would appear that the derivation of a fully explicit formula demands a knowledge of the mechanism of radiation. Planck has worked out a formula based on a special conception of atomic electrical vibrator.

On the theory of free electrons the radiation emitted by a metal is regarded as the sum total of the disturbances resulting at collision of the free electrons with atoms of the metal. When an electric charge is stopped or started, or more generally whenever it is accelerated, it becomes the centre of an electromagnetic disturbance travelling outwards in the surrounding ether. A sodium flame emits waves of a definite period, suggesting the presence in the sodium atom of electrons in regular orbital motion. But when an electron is suddenly stopped thin pulses

of electric and magnetic force travel out. Röntgen rays are generally regarded as constituted of such pulses. In the hands of Lorentz it appears that the heat radiation of a metal may be satisfactorily accounted for as being built up of pulses so generated; and by the application of Fourier analysis he has found an expression completely defining the emissivity as a function of temperature and wave-length. The theory, it must be added, is not complete. It applies only to waves of comparatively great wave-length, lying within the infra-red portion of the spectrum.

Sir J. J. Thomson has applied similar considerations to account for the fact that the spectral energy curve has a maximum at some specific wave-length depending on the temperature.

The phenomena of *thermoelectricity* may be interpreted in terms of a diffusion of electrons arising from differences in their concentration, such as occur at the junction of two dissimilar metals, or at points of differing temperature in the same metal. For such diffusion is not only a diffusion of matter, but of electricity also. Electrical forces are consequently set up which, integrated over the circuit, result in an E.M.F., the thermo E.M.F. of the circuit.

There remains for consideration a group of phenomena arising from the *influence of a magnetic field* on the flow of heat, or of electricity, in a conductor. The theory of free electrons will be found to be applicable to all these phenomena, through striking divergences between experimental facts and the consequences of the simple theory have yet to be bridged over.

In regard to the estimation of the *number of electrons* in unit volume of a metal there are some three lines of argument available. It will be seen below that the estimates are by no means in perfect agreement. One is forced to conclude that in spite of its alluring simplicity, the free electron theory should be held for the present with much reserve.

The Mechanism of Radiation.

1. *The Mechanism of Radiation.*—Sir J. J. Thomson in 1900 suggested that the radiation emitted by a hot conducting body might have its origin in the ether disturbances set up within the body when the rapidly moving free electrons collide with the atoms.

Lorentz's Theory

(1). Two or three years later Lorentz published a memoir in which this idea is worked out in detail. He considers first

the *absorption* of energy by a thin plate of the metal on which radiation is falling. If the half-period of the radiation is great compared with the period in which an electron describes its free path, the work done upon the electrons by the electric force in the incident beam is expressible in terms of the conductivity of the metal for steady currents. The coefficient of absorption is

then simply $A = \frac{\sigma}{V} \cdot \Delta$; where V = velocity of light, and Δ = thickness of plate. For the conductivity σ Lorentz derives the expression $\sigma = \sqrt{\frac{2}{3\pi}} \cdot \frac{ne^2lv}{a\theta}$. (This differs from the expression

(1) of the preceding article by the factor $\sqrt{\frac{2}{3\pi}}$; which proceeds from the fact that Lorentz adopts a more rigorous treatment of the problem of conductivity, in which Maxwell's law of distribution of velocities is employed.) Thus we have

$$A = \sqrt{\frac{2}{3\pi}} \cdot \frac{ne^2lv}{a\theta V} \cdot \Delta \dots \dots \dots (a)$$

According to this formula the absorption coefficient for a particular metal is the same for all wave-lengths, varying from one metal to another simply in proportion to the steady-current conductivity. This is certainly not true for short wave-lengths, as is demonstrated by such facts as the green colour of the light transmitted by gold leaf. The researches of Hagen and Rubens have furnished ample data for determining the range within which this assumption is applicable. They have shown that for a wave-length of 4μ the absorption coefficient of a metal is already in close agreement with that calculated from the steady conductivity, whilst at 25μ the agreement is practically complete. Lorentz considers his theory therefore to be limited to waves of length exceeding the latter value.

The next step consists in an analysis of the radiation *emitted* by the same plate. When an electron moves with acceleration f it emits radiation at the rate of $\frac{2}{3} \frac{e^2 f^2}{V}$ per second. Accelerations occur at collision of the electrons with atoms of the metal. The resultant effect of a vast number of collisions may

be submitted to Fourier analysis. The result would, at first sight, appear to depend on the law of force during collision. Lorentz assumes the period of collision to be small compared with the time of description by the electron of its free path, and by a choice of method of integration surmounts the necessity of considering the details of actual collision. The outcome of his treatment is the following expression for the emissivity E , in which λ stands for wave-length :—

$$E = \sqrt{\frac{2}{3\pi}} \cdot \frac{2}{3} \frac{ne^2lv}{\lambda^4} \cdot \Delta. \quad (b)$$

The emissivity is thus dependent on the nature of the metal and on the wave-length.

Combining the equations (a) and (b) the ratio of the emissivity to the coefficient of absorption is given by

$$\frac{E}{A} = \frac{2}{3} \frac{a\theta V}{\lambda^4}. \quad (c)$$

This is evidently independent of the nature of the metal, a result which is none other than Kirchhoff's law of radiation. Since the coefficient of absorption of a black body is unity, the expression on the right-hand side of (c) represents the emissivity E_b of the black body or full radiator.

It is convenient to state the result in terms of the radiant energy per c.c. in an isothermal enclosure. The energy comprised between two wave-lengths λ and $\lambda + d\lambda$ may be written $ed\lambda$ or $F(\lambda, \theta)d\lambda$. The quantity $F(\lambda, \theta)$ plotted as ordinate against λ as abscissa yields the spectral energy curve of a full radiator. Now E_b and $F(\lambda, \theta)$ are connected by the relation

$F(\lambda, \theta) = \frac{8\pi}{V} \cdot E_b$. We may thus write

$$F(\lambda, \theta) = \frac{8\pi}{V} \cdot \frac{2}{3} \frac{a\theta V}{\lambda^4} = \frac{16\pi a\theta}{3\lambda^4}; \quad (d)$$

which expresses the conclusion of Lorentz's analysis. It is seen to be in harmony with Wien's law as deduced from thermodynamical principles, namely $F(\lambda, \theta) = \frac{1}{\lambda^5} \cdot f(\lambda, \theta)$, where $f(\lambda, \theta)$ represents an unknown function of the product of temperature and wave-length.

It may be added that the formula (d) agrees with Planck's formula when the wave-length is large, and also with one deduced by Jeans from considerations of a more general nature.

(2). It will be seen that Lorentz's formula gives no clue as to the origin of the maximum actually found in the spectral energy curve of the black body. It shows, instead, a radiation increasing indefinitely as λ decreases: the formula is, as already stated, expressly limited to great wave-lengths.

Sir J. J. Thomson has treated the problem with a view to elucidating the conditions for a maximum. On a particular assumption as to the law of repulsive force between the electron and the atom during collision, namely, the inverse cube law of distance, he arrives at the formula

**Energy
Maximum.**

$$E = \frac{16\pi a\theta}{3\lambda^4} \varepsilon^{-\frac{4\pi V}{\lambda} \cdot \tau}, \quad \dots \dots \dots (e)$$

where τ denotes the period of collision of an electron with an atom. This will agree with Wien's formula, provided $\varepsilon^{-\frac{4\pi V}{\lambda}}$ is of the form $\varepsilon^{-\frac{h}{\lambda\theta}}$: that is, if τ is inversely proportional to θ , or to v^2 . E will then be a maximum when $4\pi V\tau = 4\lambda$, that is, when (period of collision) = $\frac{1}{\pi}$ (period of light); as the temperature rises, τ , and consequently λ_m , must change in inverse proportion—which is Wien's displacement law.

Applying the above results to the case of X-rays, generated by the impact of cathode rays travelling at a speed of 10^{10} cm. per sec., it appears that these rays should correspond with light radiation of very small wave-length. The wave-length of maximum intensity may be found as follows: The maximum in the spectral energy curve of a black body at 0°C . occurs at a wave-length of 10^{-3} cm. The speed of a free electron in a metal at that temperature is 10^7 cm. per sec. (corresponding to a period of collision of $\frac{1}{\pi} \cdot \frac{10^{-3}}{3 \times 10^{10}} = 10^{-14}$ sec. nearly). Now temperature being measured by the square of the particle velocity, a speed of 10^{10} cm. per sec. will correspond to a temperature of $273 \times 10^6^\circ\text{C}$., and the wave-length of maximum intensity will be reduced to $\frac{10^{-3}}{10^6}$, or 10^{-9} cm. The value of the wave-length of X-rays

X-Rays.

calculated in this way agrees exactly with that deduced from the recent remarkable experiments of Laue, Bragg and others on the phenomena of interference exhibited by these rays when incident on certain crystals.

2. *Thermo-electricity*.—When two different metals are placed in contact there will be a flow of free electrons across the junction from the metal containing the greater number of electrons per unit volume to the other containing the smaller number. This will leave the former positively, and the latter negatively, electrified. An electric field will thereby be set up opposing the flow, and a point of equilibrium will be reached, the two metals being then at some definite P.D. apart. The region of varying concentration will be confined to a narrow stratum extending on either side of the boundary b , an electrical double layer being thereby constituted (see Fig. 51).

A calculation of this P.D. shows that it is small. A value of 1 volt would require a ratio of free electrons per unit

The Peltier Effect.

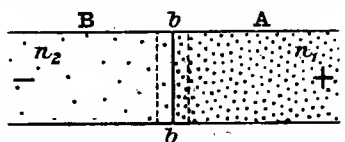


FIG. 51.—DIAGRAMMATIC ILLUSTRATION OF THE PELTIER EFFECT.

volume of the order of 10^{17} , a value quite incompatible with that required to account for the difference of conductivity between any pair of metals. Clearly the effect in question is not the Volta contact E.M.F. It is to be identified with the *Peltier* effect. Thus in the case of the couple antimony and bismuth, for which the effect is large, say $\frac{1}{30}$ volt, the ratio $\frac{n_1}{n_2}$ of electrons per c.c. works out at 3.8. The effect is of theoretical importance as indicating that the number of free electrons per unit volume does not vary greatly from one metal to another.

In connection with this phenomenon a serious discrepancy is to be noted. It arises in regard to the respective changes in electrical conductivity and in the Peltier effect which occur at fusion. The conductivities of tin, zinc and lead at their melting points

are about twice as great in the solid as in the liquid state. As there is but little change in volume—a slight contraction only—at fusion, the free paths of the electrons are hardly likely to have altered. As a reference to the formula shows, the variation of the conductivity at fusion can only be attributed to a proportional variation in the number of free electrons per unit volume. For consistency in the theory we should therefore have a comparatively large Peltier effect at the boundary of the solid and liquid metal. No such result, however, has been observed.

The mechanism of the second thermoelectric phenomenon, **The Thomson Effect.** the *Thomson* effect, is of a similar nature. A temperature-gradient in one and the same metal involves a greater pressure at the hot end than at the cold end of a bar. A flow of electrons from the hot to the cold end results; the hot end thereby becomes positively electrified, the cold end negatively (see Fig. 52). This, again, sets up an electric force from right to

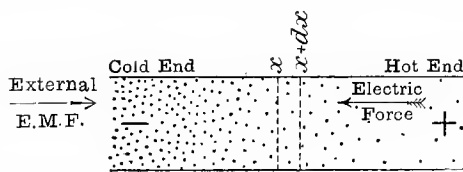


FIG. 52.—DIAGRAMMATIC ILLUSTRATION OF THE THOMSON EFFECT.

left, counteracting the migration of electricity, and a balance occurs when the pressure gradient at each point is equal to the total force due to the action of the electric field on all the electrons present in unit volume. Referring to the diagram, suppose now an external E.M.F. applied so as to drive a current from left to right. Let us consider the energy removed from or added to a stratum of width dx . The current is conveyed by electrons flowing from right to left. The electric force due to the temperature-gradient is from right to left, so that electrons must receive energy in passing across the stratum, whilst the metal within the stratum loses the same amount. This implies a *cooling* of the element of metal considered. This, however, is not the only item in the account. If the fall of temperature across the stratum is $d\theta$, each electron passes out with an amount of kinetic energy $a \cdot d\theta$ less than that with which it

entered. The defect is equivalent to the amount of heat retained within the stratum, and thus there exists a *heating* effect.

This development of heat, over and above the usual Joulean heating, which ensues when a current of electricity passes along an unequally heated conductor, constitutes the effect which Lord Kelvin, then William Thomson, foresaw from thermodynamic reasoning on the thermoelectric circuit. It is, on the free electron theory, made up of the sum of two terms of opposite sign. It appears then that the Thomson effect may be positive for some metals and negative for others (according to which of the two constituent terms preponderates), and this is well known to be actually the case. The coefficient is said to be positive (as in copper) when the passage of an electric current in the direction of the rise of temperature is attended by the absorption of heat: it is what would happen if a stream of liquid were to pass along an unequally heated tube, the tube giving up heat to the liquid if the flow is up the temperature gradient, gaining heat from the liquid if the flow is down the temperature gradient. The Thomson coefficient is indeed the exact analogue of the specific heat of the liquid; unlike specific heat, however, it is sometimes negative in value, as in iron.

The effect is found to be exceedingly small in practice; and this denotes that the two terms of which it is composed largely neutralise one another. Even in bismuth, for which the effect is comparatively large, its magnitude is only one-third of the value of the larger term. Theoretically this approximate equality of the two component terms is of much interest. It leads to a relation between temperature and the number of free electrons present in a metal. In the case of exact equality the number of free electrons per unit volume would vary as the square root of the absolute temperature. For metals in which the Thomson effect is positive the variation with temperature should be a little more rapid; where the effect is negative, a little less rapid.

The Hall Effect.

3. *Effects of a Magnetic Field.*—There is a large number of beautiful effects deducible (from the free-electron theory) in regard to the flow of electricity, and likewise of heat, in a conductor which is placed in a magnetic field. Some of these

phenomena will be briefly alluded to. Consider a current of electricity passing along a bar, as represented in Fig. 53. Let a magnetic field H be impressed perpendicularly to the plane of the diagram, the direction of the lines of magnetic force being from above below. Then if the current is conveyed by electrons travelling with speed u from right to left, each electron will experience a force Heu in the direction perpendicular both to H and the direction of the current, as indicated by the arrow a . The lower edge $A'B'$ will thus be negatively charged, owing to the presence of electrons in excess; the upper edge positively, owing to defect of electrons. A limit to the amount of this electrification is imposed by the opposing pressure-gradient which measures the tendency towards equality of distribution. There will be in the equilibrium state a transverse electric force which, integrated across the bar, constitutes an E.M.F. In practice such a transverse E.M.F. is found to exist, constituting the *Hall effect*.

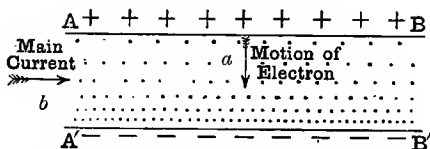


FIG. 53.—DIAGRAMMATIC ILLUSTRATION OF THE HALL EFFECT.

The complexity of the experimentally determined laws of this effect is in striking contrast to the simplicity of the theory. The latter demands an effect of the same sign in all metals, the magnitude being simply proportional to the field. Actually the sign of the E.M.F. is in some metals—*e.g.*, iron and tellurium—found to be opposite to that predicted. It is not always in proportion to the field; indeed, the sign itself may depend upon the intensity of the field. Many explanations of these apparent anomalies have been offered. Thus, in regard to iron, Sir J. J. Thomson has suggested that the reversal of sign is due to the disturbing influence of the strong field of the magnetic molecule. A. W. Smith has recently investigated the effect in this metal at temperatures above the critical temperature, but though it is much reduced he has failed to observe any change of sign.

The Nernst Effect.

The *Nernst* effect is similar to the Hall effect. In this case the phenomenon is due to the action of a transverse magnetic field on a bar through which heat is flowing; again an E.M.F. in the direction perpendicular to the direction of flow and to the field should be produced. The effect observed appears to be of the same sign in all metals, agreeing with that indicated by the theory.

The *change of electric resistance* of metals in a magnetic field is of practical interest. In bismuth it is very large and forms the basis of the well-known application of the bismuth spiral to the measurement of intense magnetic fields. According to the recent experiments of Roberts the effect in crystals of graphite is still greater. It is noteworthy that the diamagnetic susceptibility of this material is also greater than that of bismuth, hitherto regarded as the most diamagnetic substance. The explanation of the change in resistance, on the electron theory, lies in the existence of a secondary Hall effect. It will be seen from Fig. 53 that, owing to the existence of the transverse magnetic field, the motion of electrons in the direction shown by the arrow involves a force, on them in the direction opposite to that of the main flow. This is equivalent to an electric force opposing the impressed E.M.F. The current is consequently reduced in value, and we have virtually an increase of electric resistance of the conductor.

The Number of Free Electrons in Metals.

4. *The Number of Free Electrons.*—The total number of electrons in the atom of a metal is estimated to be about the same as the number expressing the atomic weight, say, 27 for aluminium, 200 for mercury, &c. On the other hand, the number of free electrons per unit volume appears to be much the same in all metals, not differing very considerably from the rate of one per atom. The following methods of determining this quantity have been employed :—

(i.) The formula for the electrical conductivity contains two unknowns—namely, the mean free path of the electron and the number of electrons per unit volume. As the distance apart of the atoms is of the order 10^{-8} cm., the mean free path of an electron may be taken to be of the order of ten times that magnitude, say, 10^{-7} cm. Assuming this, the value of n follows. Thus for silver $n=9 \times 10^{23}$; the estimate, which

cannot be regarded as more than a rough one, is equivalent to assigning five or six free electrons to each atom of the metal.

(ii.) The coefficient of absorption of radiation by a metal may be expressed in terms of its conductivity for steady currents, provided that the period of the radiation is large compared with the time taken by the electron in describing its free path in the metal. The result of increasing the period of the incident radiation is to reduce the effective conductivity to an extent theoretically calculable. Now Hagen and Rubens' experiments, already quoted (p. 122), furnish data for the variation of effective conductivity with wave-length, and thus permit of an estimate of the period between two collisions. Thus, whilst for a wave-length of 25μ the conductivity is practically the same as the ordinary steady-field value, at 4μ the conductivity has fallen by about 20 per cent. From this Sir J. J. Thomson deduces that the interval between collisions is less than one-quarter the period of light of wave-length 4μ ; and this being known, a lower limit to the average speed u of the electron in unit electric field may be arrived at. The application of the usual conductivity formula, $\sigma = neu$, then leads to a minimum estimate for n . In the case of silver, n works out to be not less than 1.8×10^{24} per c.c. Comparing this with the number of atoms 1.6×10^{23} per unit volume it appears that the number of free electrons in silver is *not less* than 11 per atom.

Estimates previously made by Drude and by Schuster, from considerations bearing on the same effect, namely the absorption of light by a metal, lead to different numbers. Drude gave the average number of free electrons per atom in silver as 1.06, in mercury 3.39, in antimony 7.54. Schuster concluded that the number per atom varies in different metals between the limits 1 and 3.

(iii.) The law of Dulong and Petit, that the product of atomic weight and specific heat is practically the same for all metals, allows of a very simple expression on the theory of electrons. Each free electron in a metal at a temperature θ is regarded as possessing a quantity of kinetic energy $a\theta$, the same as for a molecule of a perfect gas at the same temperature. The law cited above amounts to the statement that the heat energy per atom of any metal is equal to $2a\theta$. The problem now arises as to the location of this energy. Do the atoms of a solid possess

kinetic energy governed by temperature? If not, this heat energy may be attributed to free electrons associated with the atom, and the number of these per atom must be taken as two; Jeans has advanced reasons for accepting this conclusion. In any case we arrive, from Dulong and Petit's law, at a *maximum* value of two free electrons per atom of a metal.

Conclusions.

Though the three lines of argument above outlined agree in pointing to the conclusion that the number of free electrons in a metal is comparable with the number of atoms, there appears to be a real incompatibility between the limits, one a minor the other a major limit, assigned by the last two methods. Taken along with discrepancies met with here and there within the range of phenomena embraced by this comprehensive theory, there seems to be in store, to say the least, a considerable degree of mental discomfort for anyone who is content to repose on the kinetic theory of free electrons in its simple form. On the other hand, the remarkable fertility of the idea in accounting in the main for such a diversity of facts proves that it contains a substantial element of truth.

CHAPTER XIII.

MAGNETIC BODIES COMPOSED OF NON-MAGNETIC ELEMENTS.

1. Heusler, in 1903, opened a new chapter in magnetism by his announcement of the discovery of the magnetic alloys of copper, aluminium and manganese. For the first time elements which alone are very feebly, if at all, magnetic, were shown to be capable of forming when in combination a ferromagnetic body. Starting with the non-magnetic manganese-copper alloy containing about 30 per cent. of manganese, Heusler found that by the addition of a third element, which might be Al, As, Sb, Zn, or Sn, substances were produced which were strongly attracted to the poles of a magnet, and capable of retaining permanent magnetism. Binary compounds of manganese were also discovered, such as the boride, arsenide, antimonide and bismuthide, showing the same properties in a less degree. **Introductory.**

Further investigations have been carried out by Fleming and Hadfield, by Prof. Gray, A. D. Ross and other workers at Glasgow, by Wedekind, Hill, Knowlton, as well as by Heusler and his co-workers.

2. Of the tertiary alloys with copper and manganese by far the most magnetic are those in which aluminium enters as the third constituent. The best results are obtained with alloys containing approximately 63·5 per cent. of copper, 25 of manganese, and 12·5 of aluminium. As the percentage of copper is reduced the magnetic quality improves. This reduction cannot, however, in practice be carried below 60 per cent., owing to the hardness and brittleness thereby resulting. Alloys containing more than 60 per cent. of copper are amenable to working on the lathe, though forgings are not possible. **The Heusler Alloys.**

The aluminium alloy may be broadly classed with nickel and cobalt and the medium grades of cast iron. It gives the well-

known general form of **BH** curve, with **B** from 3,000 to 5,000 for **H**=150. A maximum permeability of about 200 is reached at low field strength (below 10 C.G.S.) ; the highest saturation intensity that has been measured is about one quarter of that of pure iron.

Effects of Thermal Treatment.

The coercive force, and consequently the hysteresis loss in a cycle, depend considerably on the *thermal treatment* undergone by the specimen. The effects of this treatment are very complicated, and moreover vary according to the third component present. Considerable difficulty has consequently resulted in defining the magnetic behaviour of this class of bodies ; and to this fact are attributable the apparent contradictions between the results of different observers. The behaviour of the aluminium-copper-manganese group, according to Knowlton, is as follows : These alloys possess a critical temperature, or temperature of magnetic transformation, varying between the limits of, say, 250°C. and 450°C., according to percentage composition. The change from the magnetic to the non-magnetic state appears to occur over a range of temperature ; beginning at a definite point, proceeding rapidly at first, and becoming complete at an upper limit about 50°C. higher. When the specimen is *quenched* from a temperature 50°C. to 100°C. above the upper limit, the specimen is left practically non-magnetic. If now the temperature be raised to 120°C. and maintained there for several hours, then on cooling fairly slowly to room temperature, the magnetic quality reappears to its full extent. This *ageing* quickly brings about certain favourable changes which at ordinary temperature would ensue in the course of a year or more. The effect of ageing at or just above the upper limit of transformation is generally favourable, whilst if the operation is conducted at or just below the lower temperature limit the magnetic quality is very much impoverished. Microscopic examination shows that extensive changes in crystalline structure correspond to the differences in magnetic quality.

A. D. Ross has observed that quenching from still higher temperatures greatly reduces the hysteresis. Thus a specimen after quenching showed a coercive force less than 0.3 (the value for soft iron is 1.7). Moreover, whilst the loss of magnetic susceptibility resulting from the quenching may be restored by ageing at 120°C., the low coercive force still persists. It

has been suggested by Heusler that this fact may with advantage be utilised in the substitution of these alloys for iron in iron-cored electromagnetic instruments.

The effect of *very low temperatures* has been studied at Glasgow. At the temperature of liquid air the permeability, in fields up to 200 C.G.S., may be greater by as much as 25 per cent. If the alloy has been rendered feebly magnetic by quenching from a high temperature the magnetism is largely or entirely restored on cooling to -190°C. , though this improvement is not maintained on return to ordinary temperature.

3. Heusler recorded also the existence of ferro-magnetism in certain compounds of manganese with one other element. Wedekind has added a number of such bodies to the list; and his and other researches go to show that the effective agents are true chemical compounds. The most strongly magnetic appears to be the antimonide MnSb , whose susceptibility in low fields is about one-tenth that of cast iron. The boride MnB has the greatest coercive force (33.4 C.G.S.); permanent magnetic needles of this substance may possess a strength about one-half those of ordinary steel. Other bodies of this class are MnAs , MnBi , MnP , MnN_2 , MnSn .

**Binary
Compounds.**

Wedekind has pointed out that with the single exception of nitrogen, trivalent elements combine with manganese in equal atomic proportions; and that these compounds are considerably more strongly magnetic than those into which bivalent or quadrivalent elements enter.

According to Hilpert and Dieckmann the critical temperatures of the compounds with the members of the fifth group of the periodic system are in the same order as the atomic weights:—

	Deg. C.		Deg. C.
MnP	18—25	MnSb	310—320
MnAs	45—50	MnBi	360—380

The interesting fact may be noted about the phosphide that it is magnetic on a moderately cold day, but becomes non-magnetic if held in the hand.

Data as to the magnetic properties of compounds containing Cr or V, the remaining members of the iron group in the periodic arrangement of elements, are as

yet somewhat meagre. Both elements appear to be paramagnetic, but there is evidence of the existence of ferromagnetic oxides of chromium.

**Views of
Ferro-
magnetic
Constitution.**

**Elementary
Manganese.**

4. The explanation of the magnetism exhibited by the Heusler alloys, and the other bodies containing manganese, is a matter naturally of the greatest interest. Manganese is clearly the essential constituent, and the fact of its position in close contiguity with iron, nickel and cobalt in the Periodic System suggests the existence of a "latent" magnetism which under certain conditions becomes active. It is curious that the black peroxide MnO_2 was for long known as *magnesia nigra*, on account of its supposed magnetic properties; the name manganese being thence derived to distinguish that element from magnesium.

The evidence as to the magnetic character of the element itself is not as yet free from doubt. It has generally been regarded as a paramagnetic body. The commercially pure metal is, however, but a crude product, containing some 4 per cent. of impurities, chiefly copper and iron. Weiss claims to have produced the pure metal by electrolytic reduction of MnCl_2 , using an anode of platinum-rhodium and a mercury cathode. The grey powder which resulted on driving off the mercury by heating in presence of hydrogen behaved, when compacted into a rod, as a paramagnetic body. Melted in an electric furnace composed of magnesia, in an atmosphere of hydrogen, it was found to behave as a ferromagnetic body. A BH curve was obtained showing an enormous coercive force (670 C.G.S.), and a remanent intensity one hundredth that of pure iron. Even at $\text{H}=12,000$ the specimen still remained unsaturated. This manganese appeared moreover to possess strong magneto-crystalline properties. This work affords the best positive evidence available in favour of the possession of even moderate ferromagnetism by this element.

Faraday's suggestion that possibly manganese at ordinary temperatures is above its critical point has received no experimental support. Experiments at liquid air temperatures, and quite recently by K. Onnes and Weiss at 14° abs. , have given no indication of a transformation to the ferromagnetic state. Guillaume has revived the idea in a modified form in suggesting that the Heusler alloys owe their properties to the effect of

aluminium in raising the temperature of magnetic transformation of manganese, but again the view appears to have an insufficient basis in fact.

A. D. Ross supposes the advantageous effect of other metals to be due to the separation of the molecules of the manganese, with the consequent removal of the excessively high intermolecular forces which are assumed to act in the pure metal. In support of this view evidence is adduced that the susceptibility of copper containing minute quantities of iron is far greater than that calculated from the amount of iron present.

5. Partial explanations have been attempted in the sense of locating the magnetic unit. It has long been clear that ferromagnetism is at all events not a purely atomic property. Witness the case of iron, which in the pure state and in many of its alloys is highly ferromagnetic; in ferrous sulphate and many other compounds is paramagnetic; whilst in potassium ferrocyanide and iron carbonyl it enters as a component of a diamagnetic body.

If it is determined by the molecule it becomes a matter of primary importance to discover the chemical constitution of this molecule; a problem, however, not easy to solve completely when the body is in the solid state. Heusler's most recent work leads him to regard the copper-aluminium-manganese alloys as chemical compounds of the composition $\text{Al}_x \text{Cu}_a \text{Mn}_{3x-a}$, the copper and the manganese being able to replace one another isomorphously; so that the extreme members of the series are $\text{Al}_x \text{Cu}_{3x}$ and $\text{Al}_x \text{Mn}_{3x}$, or, neglecting molecular complexity, AlCu_3 and AlMn_3 . His earlier published view that the ferromagnetic "carrier" contained Al and Mn in equal atomic proportions appears as a special case of the above formula when the initial manganese-copper alloy contains 30 per cent. of manganese: such was at first the case in his experiments, and the alloy of maximum magnetisability was found to correspond to the composition AlMnCu_2 . Ross is led to regard the above series of compounds as solid solutions of the compounds $\text{Cu}_3 \text{Al}$ and $\text{Mn}_3 \text{Al}$.

In the case of binary combinations the evidence is increasingly in support of the conclusion that they are true chemical compounds of the elements concerned. As noted already, the

**The
Magnetic
Unit.
Is it Atomic ?**

**Or
Molecular ?**

most magnetic bodies of this class are those in which manganese figures as a trivalent element. Other examples of the importance of chemical form appear. Magnetic oxide of iron, Fe_3O_4 , may be regarded as a ferrite $\text{FeO} \cdot \text{Fe}_2\text{O}_3$. The FeO may be replaced by CoO or CuO , and the resulting cobalt and copper ferrites are likewise strongly magnetic. Other compounds of the same class are known, in all of which the strong magnetisability appears to depend on the acid function of the ferric oxide Fe_2O_3 .

Or an
Association
of Molecules?

The simple view that the molecule determines the ferromagnetism is, however, difficult to hold in view of the enormous effects of thermal treatment. Hopkinson's nickel-steel may be practically non-magnetic or highly magnetic at the same temperature, according to treatment. The same applies to some of the manganese steels, and, though perhaps in a less degree, to the Heusler alloys. Now it has been shown that the *microstructure* of these bodies varies greatly with change of magnetic condition. Thus has arisen the theory of the association of molecules in some definite crystalline formation. Given the right kind of atom, in the right kind of molecule, in the right kind of crystal, and we have the unit of ferromagnetism. The process of ageing may be regarded as the slow formation of the magnetic molecule and the simultaneous building up of these into the requisite kind of space-lattice; or, more simply, as the latter change only, the correct geometrical association of molecules. In other words, temperature may be held to affect the molecule itself, or only the manner of association of the molecule. This association, furthermore, may be one of polymerisation, or one on a far larger scale—namely, crystal formation.

Further experimental data are needed to throw light on the problem of the constitution of the ferromagnetic body.

